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ASSESSING THE UTILITY OF AN EVENT-STEP ASMD MODEL BY ANALYSIS OF SURFACE COMBATANT SHARED SELF-DEFENSE

by

Chase D. Patrick

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Thesis Advisor:	Wayne P. Hughes, Jr.
Second Reader:	Arnold A. Buss

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Anti-ship cruise missiles (ASCMs) are increasing in quantity, capability, and availability throughout the world, posing a significant threat to United States naval forces operating in littoral waters. The improving performance and growing availability of ASCMs makes a persuasive argument for the U.S. Navy to aggressively expand surface combatant defense systems, and perform periodic reviews of existing defensive tactics to ensure effective employment of new combat systems. To guide decision makers in both of these areas, simulation and modeling tools are frequently applied. This thesis assesses an event-step Anti-Ship Missile Defense (ASMD) model through the evaluation of two new hardkill weapon systems, the Evolved Seasparrow Missile (ESSM) and an improved Rolling Airframe Missile (RAM). The performance of both systems will be evaluated within the context of a single-ship and a multi-ship formation responding to ASCM attacks. The goal of this thesis is threefold, namely to assess the effectiveness of additional anti-ship missile defense systems and identify any tactical insights derived from the modeling results of the multi-ship formation. Following these employments of the model, an evaluation is made regarding the use of the ASMD model as a tool for the tactical commander.

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ASSESSING THE UTILITY OF AN EVENT-STEP ASMD MODEL BY ANALYSIS OF SURFACE COMBATANT SHARED SELF-DEFENSE

Chase D. Patrick
Lieutenant, United States Navy
B.A., University of Virginia, 1994

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September 2001

Author: ______________________
Chase D. Patrick

Approved by: ______________________
Wayne P. Hughes Jr., Thesis Advisor

____
Arnold A. Buss, Second Reader

____
James N. Eagle, Chairman
Department of Operations Research

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ABSTRACT

Anti-ship cruise missiles (ASCMs) are increasing in quantity, capability, and availability throughout the world, posing a significant threat to United States naval forces operating in littoral waters. The improving performance and growing availability of ASCMs makes a persuasive argument for the U.S. Navy to aggressively expand surface combatant defense systems, and perform periodic reviews of existing defensive tactics to ensure effective employment of new combat systems. To guide decision makers in both of these areas, simulation and modeling tools are frequently applied. This thesis assesses an event-step Anti-Ship Missile Defense (ASMD) model through the evaluation of two new hardkill weapon systems, the Evolved Seasparrow Missile (ESSM) and an improved Rolling Airframe Missile (RAM). The performance of both systems is evaluated within the context of a single-ship and a multi-ship formation responding to ASCM attacks. The goal of this thesis is threefold, namely to assess the effectiveness of additional anti-ship missile defense systems and identify any tactical insights derived from the modeling results of the multi-ship formation. Following these employments of the model, an evaluation is made regarding the use of the ASMD model as a tool for the tactical commander.

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THESIS DISCLAIMER

The reader is cautioned that computer programs developed in this research may not have been exercised for all cases of interest. While every effort has been made, within the available time, to ensure that the programs are free of computational and logic errors, they cannot be considered validated. Any application of these programs without additional verification and validation is at the risk of the user.

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TABLE OF CONTENTS

LIST OF FIGURES

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LIST OF TABLES

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I would like to express my gratitude and acknowledge the Johns Hopkins University Applied Physics Lab (JHUAPL), specifically the departments for Air Defense Systems and Joint Warfare Analysis. Both the staff and faculty demonstrated great hospitality, and superb guidance was provided to myself as I attempted to learn the nuances of Air Defense theory and the systems involved. It was during my experience tour at JHUAPL that my research generated an idea that eventually evolved into this thesis. I would also like to thank the James Townsend, the developer of the ASMD model, for his patience and support as I struggled to learn the inner operations of a very ambitious model. I am grateful to Professor Wayne P. Hughes, Jr., Captain, USN(Ret.) and Professor Arnold A. Buss for their encouragement and direction while completing this work, and for introducing me to exciting aspects of Operations Research of which I had little experience. And finally, I wish to express my deepest gratitude and affection to my wife Paurenia, who slowed my progress by giving me two enchantingly beautiful children. Everything I do, I do for them, and their encouragement carried me throughout this process.

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EXECUTIVE SUMMARY

Though the capabilities of the modern surface combatant are significant, particularly when exercised within the context of a formation of ships, the threat posed by modern Anti-Ship Cruise Missiles (ASCM) in littoral waters is greatly accentuated. This is due to the reduction of battle space and warning time that results from proximity of land and the relative confinement posed by such proximity or coastal layout, dense commercial air and maritime traffic, and the potential use of land-based electronic countermeasures (ECM).

To operate effectively in this environment, the self-defense capability for individual surface combatants must be expanded and enhanced. The ever-increasing capabilities of ASCMs cannot be totally deflected by the mere presence of an AEGIS warship providing area defense coverage, nor can a Standard Missile (SM) effectively compete with all present and future ASCMs.

To combat the uncertainty that exists regarding the effectiveness of current and future defensive missile systems against future threat ASCMs, modeling and simulation tools are often applied. Such models range from the high-resolution naval combat model to the aggregated campaign model, and all types have been applied to answer questions related to surface combatant air defense. But there are very few models that account for the effects of naval screen formation on defense, or model realistically the manner in which missiles choose their targets. This is the area that the Townsend Anti-Ship Missile Defense Model (ASMD) seeks to fill.

The ASMD model ambitiously attempts to model missile kinematics realistically, and handles targeting by accounting for direction of motion, screen design of the naval formation, the size of the targets in the formation, and missile altitude. The goal of this thesis is threefold, namely to assess the effectiveness of new anti-ship missile defense systems and identify any tactical insights derived from the modeling results of the multi-ship formation. Following these employments of the model, an evaluation is made regarding the use of the ASMD model as a tool for the tactical commander.

To determine if the ASMD model is providing reasonable outcomes, two groups of simulation are studied. The first group of simulations is designed to assess the effectiveness of future anti-ship missile defense systems against a future ASCM threat.

This is accomplished by modeling a single Anti-Air Warfare (AAW) capable ship that independently employs each missile system in its defense against varying salvo sizes of ASCMs. Results for this first series of simulations reinforce the superiority of a Shoot-Shoot-Look firing doctrine, and suggest it is highly possible to model missile systems in the ASMD model and obtain the anticipated outcomes.

The second group of simulations modeled a three-ship naval fomation defending against an ASCM attack. The formation consisted of an AAW-capable ship and two larger amphibious ships, and the purpose was to assess the role of screen design on shared self-defense. The outcome revealed a the model was not as sensitive to range as expected with respect to the stationing of the AAW ship from the amphibs, but did reinforce the notion that stationing the AAW ship on or near the threat axis provided the optimal defense opportunities.

The ASMD model is ambitious in design, and has achieved much of what its designer intended. However, more work is required in several areas of weakness that were uncovered during the exercise of the model. These areas include the tendency of the model to freeze in mid-simulation, and the perfect detect-to-engage sequence for the surface combatant that tilts the playing field away from the ASCM and provides significant advantages to the defensive missile systems employed. But the ASMD model makes significant progress towards providing the decision maker with a model that incorporates real tactical considerations that are daily faced by naval operational forces projecting power in a littoral environment.

I. INTRODUCTION

When operating in littoral waters, such as the Northern Arabian Gulf, the proximity of surface combatants to hostile shores demands that ship self-defense requirements be stringent. The United States Navy (USN) is still in the process of transitioning from a blue-water fleet to a fleet with expanded capability for operating in littoral waters. This transition is largely attributed to the decline of the former Soviet Union and the subsequent massive proliferation of advanced technologies to Third World nations, and is driven largely by the pivotal 1992 publication of *From the Sea*. The primary threat to surface combatants comes in the form of missile-laden patrol boats and mobile truck-launched cruise missiles, as well as some limited capability with regard to military aircraft.

Though the capabilities of the modern surface combatant are significant, particularly when exercised within the context of a formation of ships, the threat posed by modern Anti-Ship Cruise Missiles (ASCM) in littoral waters is greatly accentuated. This is due to the reduction of battle space and warning time that results from proximity of land and the relative confinement posed by such proximity or coastal layout, dense commercial air and maritime traffic, and the potential use of land-based electronic countermeasures (ECM). The security of naval operations in the open ocean largely results from an advantageous combination of depth of fire, isolation, and superior surveillance systems and techniques. This advantage declines steeply in the littorals, particularly for surface combatants operating away from the battle group and performing operations such as picket, interdiction, minesweeping, and land attack.

To operate effectively in this environment, the self-defense capability for individual surface combatants must be expanded and enhanced. The ever-increasing capabilities of ASCMs cannot be totally deflected by the mere presence of an AEGIS warship providing area defense coverage, nor can a Standard Missile (SM) effectively compete with all present and future ASCMs (Ousbourne, 1993). Early ASCMs were subsonic threats designed for low-altitude approaches on target ships. The cruise missile threat challenging the modern navy includes characteristics such as supersonic flight, preplanned evasive maneuvers, radar cross-section reduction, and multimode guidance (Graff, 1999). Meanwhile, the littoral warfare environment often results in warships operating independently or in groups of two or three, and proximity to the enemy threat significantly reduces reaction time to an ASCM launch. In view of the challenges posed by the modern ASCM and the littoral environment, the Standard Missile is losing its advantage for force defense. A partial solution is to upgrade the self-defense capability of all surface combatants. The Navy is already proceeding in this direction with the development of the Ship Self-Defense System (SSDS), the Evolved Seasparrow Missile (ESSM), and the Rolling Airframe Missile (RAM).

Where the SSDS provides integration of sensor and weapon systems to grant non-AEGIS platforms an automated response system, the ESSM and RAM are intended to improve point defense and close-in defense respectively. These latter additions are intended to make up for performance deficiencies of Standard Missile and the Close-in Weapon System (CIWS) by offering increased kinematics, faster fly-out, supersonic flight, and multimode seekers (semi-active homing and infra-red (IR) terminal homing). This study places a spotlight on the future employment of ESSM and RAM.

The addition of these two assets onboard surface combatants requires an exploration of the doctrine that exists behind their use, specifically, firing doctrine and salvo policy against ASCM threats in the littoral. The platforms of choice for this study include a ship equipped with the Mk 41 Guided Missile Vertical Launch System (GMVLS), namely a Ticonderoga-class Aegis cruiser, and a representation of an amphibious ship armed only with the RAM system. These choices represent a desire to model existing platforms that represent high and low levels of self-defense capability. The importance of GMVLS is due to its real role as the future launcher system for ESSM, while RAM possesses an independent launcher. Firing doctrine and salvo policy, in combination with the orientation of the ship formation relative to the threat axis, will be examined against the threat of a supersonic low-flyer.

A. BACKGROUND

The ASCM threat arose early in the Cold War, leading to the development of surface-to-air missiles (SAMs) that saw initial forays into defensive TALOS, TERRIER, and TARTAR SAMs. Most ominous was the threat from nuclear warhead-tipped ASCMs developed by the Soviets early in the Cold War, which influenced everything from ship design to unit formations. Despite the fading of the nuclear threat, its influence on modern warship design is still prevalent despite the obvious vulnerabilities (e.g., a lack of armoring) to conventional weapons that afflict staying power of the Surface Fleet to this day. (Hughes, 2000)

The Egyptians were the first to launch an ASCM against a ship, sinking the Israeli picket-destroyer *Eilat* in a 1967 attack. Other major events in which ASCMs played a significant role were the 1973 Arab-Israeli War, the 1971 Indo-Pakistan War, the 1982 South Atlantic War, and the Tanker Wars of the 1980's. Many other ASCM attacks since the *Eilat*, of varying scope, have also provided the analyst with valuable data in addition to the previously mentioned events. A study authored by John Schulte (1994) utilized actual ASCM data from the above-mentioned historical episodes, in which he recorded missile attacks and measured their effectiveness from the perspective of the attacker. Wayne Hughes (2000) provided a useful summary and interpretation of Schulte's and several other studies affecting warship staying power in the face of an ASCM threat.

Numerous modeling methods have been used to answer questions regarding surface combatant self-defense. Jerren Gould (1984) examined salvo policies against enemy air, demonstrating that with the non-decreasing probability of a single-shot kill, the sequence of salvo sizes that minimize the expected number of shots used is also non-decreasing. Mark Jarek (1988) utilized a spreadsheet methodology to determine an optimal VLS load-out for ship self-defense against ASCMs, examining a force with and without Combat Air Patrol (CAP) available. Jeffrey Cares (1990) sought to describe the characteristics of modern salvo warfare after applying several closed-form modeling options to a robust data set, and provided suggestions regarding tactical employment of forces. Arthur Drennan (1994) applied a linear programming method to propose a coordination policy for NATO Seasparrow Missile (NSSM) and RAM against ASCMs, while Hughes (1995) describes his missile salvo equations for warships in combat for the purpose of comparing the primary combat characteristics of a warship.

Of principal importance to this thesis is the work by James Townsend (1999), who developed the Anti-Ship Missile Defense (ASMD) model. His object-oriented, event-stepping model simulates the entire process by which ASCMs select their targets, and by which defenders assign defensive fire. His purpose was to create a model that can be used to examine screen design and defensive firing doctrine for naval formations.

B. PROPOSED DEFENSIVE MISSILE SYSTEMS

Commander Glenn Flanagan, USN, asserts that the threat to surface ships is increasing as a result of two factors in modern naval operations. The first is the proliferation of ASCMs; the second is the prolonged periods of operation in littoral waters previously discussed in this thesis. Regarding the former point, Flanagan cites seventy nations that currently deploy sea- and land-launched ASCMs, and greater than 20 that possess air-launched ASCMs. Many of these countries do not have any ability to produce this level of technology, relying on imported missiles with Russian, Chinese, or French origins. The advantage for foreign nations is a powerful and relatively inexpensive method to contest a superior naval force. (Flanagan, 1999) Probably the most difficult ASCM for the U. S. Navy to defend against is the Russian-produced supersonic Moskit (SS-N-22) missile. More popularly known as the Sunburn, it can be launched from land or naval platforms, and recently has been documented as an exported technology to the People's Republic of China (PRC) in 2000. (Gertz, 2000)

In the face of this mounting ASCM threat, part of the Navy's strategy to keep pace with the Ship Self-Defense Capstone Warfighting Requirements, encapsulated within a 1995 review, is to procure the ESSM and RAM systems.

1. Evolved Sea Sparrow Missile (ESSM) System Characteristics

The Evolved Sea Sparrow Missile (ESSM) is a medium range missile designed to offer greater self-protection for surface ships. Its capabilities are expected to exceed the performance of Standard Missile-2 (SM-2), the Navy's primary surface-to-air fleet defense weapon, particularly against low observable extremely maneuverable missiles. A substantial upgrade of the NATO Sea Sparrow (RIM-7P) Missile System (NSSMS), the ESSM has greater range and speed and can make flight corrections via radar and midcourse uplinks.

On Aegis ships, ESSM will be launched from Mk 41 VLS Quad Pack canisters that will allow an even greater defense missile load-out. The guidance section is virtually the same as its predecessor, but the new rocket motor offers higher thrust, and steering is achieved with tail control vice wing control. Table 1 details the physical features of the weapon (Nicholas & Rossi, 1999).

Evolved Sea Sparrow Missile (ESSM)			
Dimensions:		**Performance:**	
Length	12.0 ft	Max Range	16 nm
Diameter	8 in	Altitude	16,405 ft
Span	3.3 ft open / 2.1 ft folded	Speed	Mach 5.0
Weight	620.0 lbs		
Guidance: command guidance			

Table 1. Evolved Sea Sparrow Missile (ESSM) characteristics.

2. Rolling Airframe Missile (RAM) System Characteristics

The goal of the Rolling Airframe Missile (RAM) is to provide surface ships with a highly effective, low-cost, point-defense system that offers a significant capability to engage and kill incoming ASCMs. The airframe rolls in flight for stability and is guided by dual mode, passive radio frequency/infrared (RF/IR) guidance. Initial homing is in RF, with transition to IR guidance when an ASCM's IR radiation is acquired. An upcoming RAM Block 1 IR upgrade will permit IR "all-the-way-homing" guidance. For cruisers, destroyers, and possibly frigates, the launcher most likely will not be the 21-cell Mk 49 launcher, but rather a proposed upgrade to the existing CIWS mount called Sea RAM. Sea RAM features an 11-cell launcher, and would retain the Phalanx system radars and FLIR. Table 2 details the physical features of the weapon (Nicholas & Rossi, 1999).

Rolling Airframe Missile (RAM)			
Dimensions:		**Performance:**	
Length	9.2 ft	Max Range	5 nm
Diameter	5 in	Altitude	n/k
Span	1.4 ft	Speed	Mach 2.0
Weight	162.0 lbs		
Guidance: dual mode passive RF / IR homing			

Table 2. Rolling Airframe Missile (RAM) characteristics.

C. OBJECTIVE

The goal of this thesis is threefold, namely to assess the effectiveness of new anti-ship missile defense systems and identify any tactical insights derived from the modeling results of the multi-ship formation. Following these employments of the model, an evaluation is made regarding the use of the ASMD model as a tool for the tactical commander. The broad expectation is that the ASMD model will affirm that the addition of ESSM and RAM will offer the tactical commander increased self-defense capability and greater flexibility with respect to the orientation of the formation to the threat axis.

Among the issues not broached by this thesis are procurement analyses, evaluation of ship modernization requirements, and optimum missile load-out strategies. Each one is very important and being aggressively pursued by the Navy, whereas the primary focus of this study concerns tactics, defined by Hughes (2000) as the handling of forces in battle.

The extensive series of simulations performed fall into two phases. The first phase is largely proof of concept in which the ASCM threat is directed against a single ship. The goal was to test the effectiveness of ESSM and RAM additions to the surface ship arsenal, as well as observe ASMD model behavior after parameterization of key variables. The second phase of simulations focuses on a multi-ship formation defending against the ASCM threat. The formation consists of two generic amphibious-class vessels escorted by an Aegis cruiser. The purpose is to identify what formation orientation relative to the threat axis is most helpful or hurtful to shared self-defense.

Several MOEs are proposed to evaluate the model's various outcomes. The first concerns the percentage of enemy missiles destroyed, and the second tracks the number of ASCM hits against a target ship.

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II. ANTI-SHIP MISSILE DEFENSE (ASMD) MODEL

A. ASMD MODEL BACKGROUND

James Townsend notes that there exist a significant number of computer models to simulate ship defense against ASCMs, but few provide any insight on the role of screen defense. Some of these models simulate defensive fire by a single ship, including among them the Single Ship Air Defense Model (SSDAM) and the Simulation, Evaluation, Analysis, and Research on Air Defense Systems (SEAROADS) model. Occupying the other end of the spectrum are aggregated campaign models such as the Integrated Theater Engagement Model (ITEM) and the Extended Air Defense Simulation (EADSIM). The single-ship models provide reasonably good analyses but cannot be extended to multi-ship formations, while the campaign models do not faithfully model screen design or firing policy effects. In the case of ITEM, missile raids are equally divided amongst the ships in a targeted formation, followed by the application of Monte-Carlo methodology to determine if a ship has sustained a missile hit. (Townsend, 1999)

The issues of portability and ease of use are applicable as well. Using the previously mentioned models above as examples, they would not serve well as tools to the tactical commander responsible for the employment of two or more combatants. The single-ship models cannot be made relevant due to the inability to model more than one ship. The campaign model certainly can capture all of the pertinent details, but is handicapped by the amount of data and computing capacity required, the complexity involved in scenario generation, and requisite operator expertise. None of these models supply the simplicity and relevance sought by the naval officer who desires a quick analysis to support an upcoming straits transit, for example. This is the problem that Townsend sought to address.

B. ASMD MODEL APPLICATIONS

Townsend (1999) suggested possible applications of his ASMD model for hardware acquisition, force structuring, evaluation of the capability of forces, and tactical development. It is the latter application addressed in this thesis for the purpose of gaining useful observations on the behavior of the ASMD model.

The primary goal of Townsend's (1999) thesis efforts was to develop a model that employed a more realistic missile distribution pattern. This pattern finds its basis in the actual geometry data perceived by each inbound missile. However, no serious application of the ASMD model has been attempted yet. Townsend demonstrated some of the analysis opportunities by running an ASCM attack scenario on a standard carrier task group to determine the best screen arrangement and defensive firing policy.

C. ASMD ENTITIES

The source of the ASMD model's construction is the Java programming language, with much of the foundation built upon the burgeoning library of Java simulation components developed at NPS. Specific simulation libraries employed are Simkit and Modkit. Simkit's developer was Kirk Stork (Stork, 1996), and Modkit arrived several years later following the efforts of Arent Arntzen (Arntzen, 1998). In both cases was guidance provided by Professor Arnold A. Buss of the Operations Research Department.

It is a characteristic of Java to support object-oriented programming (OOP), a methodology that promotes objects (such as simulated ships and missiles, as in the case of this thesis) interacting with each other through the use of methods (or actions). This feature is a great benefit to any future user of the ASMD model who might desire to build a new missile object or class of ship.

Objects in the ASMD model originate from the Composite Unit, a generic object with special functional components. These components include a controller that directs the assorted functions, such as movement, sensors, and the ability to interact with other objects that results in behavioral change (such as a ship reacting to detection of missiles). Drawing the Composite Unit's properties together into a useful object is the TacticalUnit, allowing the disparate components to behave as one entity. The TacticalUnit object is the template from which missiles and ships are created.

Sensor systems for ships and missiles are fairly simple to construct, where the primary feature is maximum theoretical range. Ships may include multiple active or passive sensors.

In the case of distinct missile systems, these may also number more than one per ship. Defensive gunfire, as in the case of CIWS, along with passive defense methods, are aggregated into a numerical probability of an ASM not striking the ship. This is due to the desire to focus primarily on missile-on-missile defense. (Townsend, 1999)

D. ASMD MODEL DEFENSIVE FIRE LOGIC

The ASMD model is currently configured to adjudicate defensive battles, and each side is assigned a FireDistributor that performs missile fire decisions. Sensor detection of a new target results in the identity of that target being passed to the FireDistributor, which searches through the available ships to determine the one with the best opportunity for target intercept.

Several mediator functions referee the behavior between individual missiles and their targets. Mediators determine whether a target goes detected or undetected, track the movement of a target while guiding the missile to intercept it, plan the detonation, and assess the outcome, all with Monte Carlo generated probabilities.

The first of three possible outcomes that occur following missile detonation is a miss due to the physical range between missile and target being too great. The second is that the target sustains a missile hit, while the third outcome is missile destruction due to defensive fire or passive measures.

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III. PROBLEM DESCRIPTION

There are few, if any, ship defense models that feature the tactical role of screen design as a tool against ASCMs. The ASMD model makes up for this deficiency by generating rational missile distribution patterns that are dependent on the screen formation. The model will be applied to evaluate the effectiveness of future ship defense systems, notably ESSM and RAM, against a homogeneous ASCM attack. Insight will be sought regarding how well the new systems complement screen formation design, and firing policy will be validated as well. Several measures of effectiveness (MOEs) are proposed to evaluate the model's various outcomes. The first concerns the percentage of enemy missiles destroyed, and the second tracks the number of ASCM hits against a target ship.

A. DESIGN OF EXPERIMENT

The physical characteristics of ESSM and RAM have been previously discussed, and the future employment of each are geared toward improving a surface ship's layered defense and flexibility in response.

In general, the extensive series of simulations performed fall into two phases. The first phase is largely proof of concept in which the ASCM threat is directed against a single ship. The goal is to test the effectiveness of ESSM and RAM when added to the surface ship arsenal, as well as to identify ASMD model behavior following parameterization of key variables. The second phase of simulations focuses on a multi-ship formation defending against the ASCM threat. The purpose is to identify what formation orientation relative to the threat axis is most helpful or hurtful to shared self-defense.

B. THE SINGLE-SHIP PROBLEM

The purpose of the single-ship problem is largely proof-of-concept, specifically, to test each missile system independently of any other for improvement in its respective layer of ship defense. The platform selected for study is an Aegis cruiser outfitted with Mk 41 GMVLS, and the means of defense to be evaluated independently and sequentially are SM2ER, ESSM, and RAM. Passive defense measures are also factored in, while CIWS is not included, for reasons to be explained below.

Figure 1 depicts the concept of engagement zones for RAM, ESSM, and SM2ER. The diagram illustrates that each missile has a limited range, the shortest belonging to RAM at approximately 5 nautical miles (nm), ESSM slightly greater at 16 nm, and SM2ER with the greatest estimated range at 100 nm.

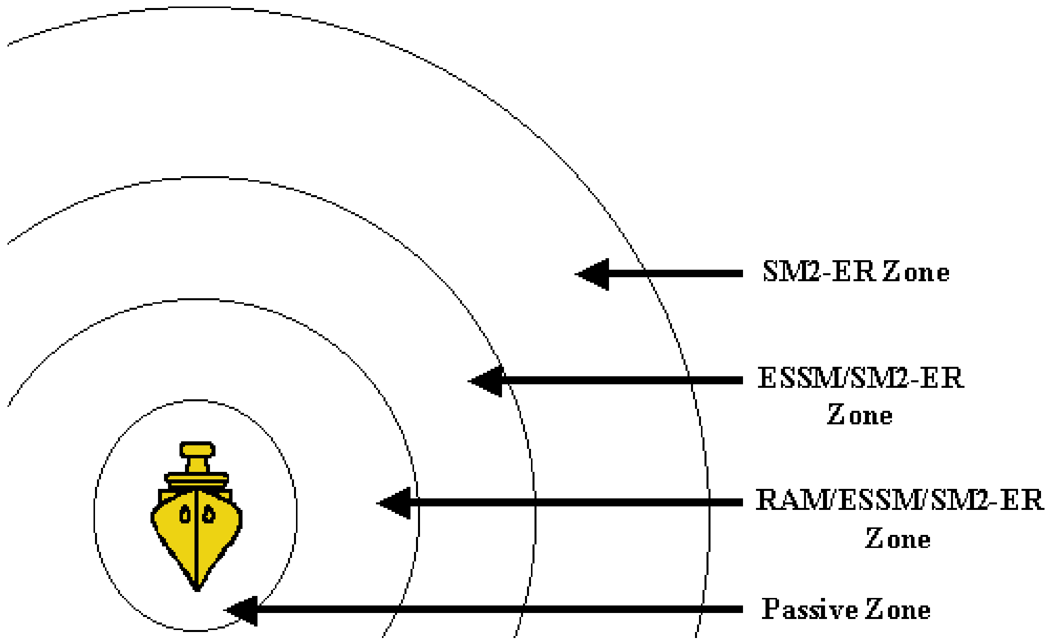

Figure 1. Engagement zones for RAM, ESSM, and SM2-ER.

1. Scenario Basics

To meet the goals of the preliminary phase of simulation, a simple scenario was devised to consist of an ASCM salvo fired down a single line of bearing (LOB) at an Aegis cruiser. The cruiser is set on a course and speed of 000T at approximately 13 knots, and the ASCM salvo is fired from a relative bearing of 270. The assumptions regarding the cruiser's state of readiness are that the ship is alert with 100 percent system availability. One ASCM hit will put the cruiser out of action (OOA) and unable to employ hardkill methods, but softkill is still available.

The system not included in this study is CIWS. One reason has to do with the realistic limitations of CIWS, specifically that it is good for one engagement alone. The second reason involves its expected replacement by the more effective RAM system. CIWS is probably fairly effective against an older generation of ASCM, but arguably less so against the terminal maneuvers of the newer breed of supersonic low-flyers. A third reason is the desire to keep the scenarios simple by focusing on hardkill by missile systems.

2. Assumptions Concerning RAM, ESSM, and SM2-ER

The ASMD model maintains a simple approach towards ASCM detection and tracking: that all threat missiles in a salvo are detected and successfully tracked once in sensor range.

The delay between SM2-ER and ESSM launches is set for one second due to the effectiveness of the Mk 41 VLS. In the case of RAM, there is a fratricide issue due to the IR terminal homing characteristic of the missile. With this in mind, a launch cycle delay of four seconds was set. In all three cases, the launch delay is intended to be a representative value rather than a true indication of system performance.

The Probability of Kill (PK) is a specified constant for each missile throughout its respective engagement envelope. This means that range-dependent PKs are not applied in the ASMD model. The respective PKs for SM2-ER, ESSM, and RAM are 0.5, 0.6, and 0.7. Each missile is expected to be a highly effective weapon system against future ASCM threats, so a conscious decision was made by the author to reasonably undervalue the PK of each missile against the particular ASCM threat described below. Furthermore, the PKs represent the relative effectiveness expected from each layer of defense, such that RAM is a relatively better ASCM killer than SM2-ER.

3. Assumptions Concerning Softkill

Hughes discusses the effectiveness of softkill measures in Fleet Tactics, and through the analysis of historical data, is able to suggest that a combat-ready ship employing passive defense can enjoy a greater than 0.6 probability of not sustaining a hit by an ASCM (Hughes, 2000). With this in mind, a softkill probability of 0.5 is assigned to the cruiser. The true effectiveness of softkill measures against the modern ASCM, supersonic or otherwise, is assuredly classified. Knowing the historical numbers, and assuming technology improvements in both softkill and ASCMs, it is entirely reasonable to assign a value of 0.5.

After all the scenarios are run and the data is analyzed, it may appear that a disproportionate advantage has been afforded to either side of the missile exchange. If this is the case, then the adjustment of this value is a good place to begin for the purpose of tilting the playing field in any manner the user may find necessary. Provided to ASCM has survived the defensive missile fire of the ship, a smaller value will afford the ASCM greater opportunities to achieve a hit.

4. The Threat

The most likely ASCM threat to be encountered by today's naval force is a subsonic missile, particularly the French-made Exocet. However, for the purpose of this study, an evaluation of anticipated ship defense systems against a more challenging ASCM is warranted, namely a supersonic low-flyer. Table 3 details some of the fixed data applied to the threat ASCM modeled for the scenario.

Notional Supersonic Low-Flyer ASCM	
Performance:	
Max Range	50 nm
Cruise Altitude	20 m
Terminal Altitude	7 m
Speed	Mach 2.5
Guidance: active radar seeker in terminal phase	

Table 3. Fixed data applied to modeled threat ASCM.

5. Variables

For each variation of the standard scenario, the defensive battle is run five times in order to reduce variation somewhat. It would be preferable to run each variation of the battle more than five times; however the large number of simulations, and the time requirements for each run, forces the constraint. The standard scenario features five primary independent variables that were altered for the purpose of testing the ASMD model's sensitivity. These include the range of the ASCM launcher to the cruiser, ASCM raid size, ASCM Probability of Hit (Phit), ASCM launch cycle time, and the cruiser missile defense available. Table 4 displays the matrix of variables altered for each simulation run. Based on the information presented in the table, the number of distinct simulations that were run in support of this portion of the study is 486.

1	**Range (nm)**	1	15
		2	25
		3	35
2	**Raid Size**	1	2
		2	4
		3	8
3	**ASCM Phit**	1	0.7
		2	0.75
		3	0.8
4	**ASCM Launch Rate**	1	1 sec
		2	4 sec
		3	8 sec
5	**Cruiser Defense**	1	SM2-ER (SSL/SLS)
		2	ESSM (SSL/SLS/SingleShot)
		3	RAM (SingleShot)

Table 4. Simulation matrix of variables for single-ship problem.

a. Range

The range between the ASCM launcher and the cruiser was varied among three values: 15, 25, and 35 nautical miles. The purpose of varying range is to test the ASMD model and determine if it meets expectations. Specifically, the closer the ship is to a coastal or sea-based ASCM launcher, the shorter the reaction time and less likely the ship can defend against an attack. The cruiser should sustain more hits as the range decreases.

b. ASCM Raid Size

The ASCM raid size is varied from a choice of three values: 2, 4, and 8 ASCMs. A conscious decision was made to model raid sizes with values that would not be much greater than real world expectations. The larger ASCM salvoes should result in more hits on the cruiser, particularly when launched at close range.

c. ASCM Probability of Hit (Phit)

There are three values that can be assigned to the ASCM: 0.6, 0.75, and 0.8. When an ASCM survives the defensive battle, it will score a hit on the cruiser with the assigned probability.

d. ASCM Launch Cycle Time

The rate of fire by the ASCM battery is varied to assume values of one, four, and eight seconds. The shorter the interarrival time of the threat stream, the greater should be the difficulty for the cruiser to successfully engage all ASCMs in the salvo.

e. Cruiser Missile Defense

Each simulation run features only one of the three surface-to-air missiles available to the cruiser, namely SM2-ER, ESSM, or RAM, supplemented by a softkill capability. Within this variable, firing policy is tested as well. SM2-ER is simulated with both Shoot-Shoot-Look (SSL) and Shoot-Look-Shoot (SLS). ESSM is simulated with SSL, SLS, and SingleShot (S). RAM is simulated with SSL and S. ESSM and RAM are forecast to be very potent systems against low flyers, so SingleShot is tested in both cases to determine if effectiveness is sufficient. It was further decided to not run simulations with RAM applying SLS, due to the significant time delay between launches (following fratricide concerns) and the short intercept ranges of this system.

6. Data Collection

The executable program of the ASMD model is coded so that each of the 486 distinct simulations run is repeated five times. This allows for data to be generated, from which measures of effectiveness can be determined. Possible MOEs are:

a. Number of ASCM hits on a ship.

b. Number of ASCMs that achieve homing on a ship.

c. Number of shots taken at ASCM.

d. Number of ASCMs attrited by missile shots.

e. Number of ASCMs attrited by softkill.

For each of these potential MOEs, the data available for analysis are the mean, standard deviation, maximum value, and minimum value.

For this phase of the study, the utilized MOEs are the number of ASCMs attrited by missile shots, and the number of ASCM hits on a ship. Broadly, it is anticipated that the data will demonstrate an improvement in self-defense for the cruiser through employment of ESSM and/or RAM over SM2-ER alone.

C. THE MULTI-SHIP PROBLEM

As Hughes (2000) states in his discussion of fleet tactics, "position relative to the enemy is still a vital tactical ingredient" and shall serve as the basis for this second phase of study. The addition of new technologies, specifically RAM and ESSM, to a ship's arsenal has great potential for influencing the tactical positioning of one or more ships. The proposed scenario consists of a notional amphibious readiness group (ARG) containing two generic amphibious-class ships and an Aegis cruiser operating in mutual defense. The Aegis cruiser is arguably the most capable combatant for waging an offensive or defensive battle, while the amphibs possess only a self-defense capability consisting of RAM and softkill measures.

1. Scenario Basics

The scenario applied in the single-ship problem was modified for the three-ship instance, in which one of the amphibs is assigned the role of formation guide. As before, the ASCM salvo is fired down a single line of bearing (LOB) at the ship formation. The formation is set on a course and speed of 000T at approximately 13 knots, and the ASCM salvo fired from various relative bearings. The assumptions regarding the state of readiness for all ships are that they are alert with 100 percent system availability. One ASCM hit will put any ship out of action (OOA) and unable to continue the defensive battle with hardkill systems.

All of the assumptions regarding SM2-ER, ESSM, and RAM remain intact from the single-ship scenario. The only variation regarding missile systems is for the amphibs. Only the cruiser will be modeled with SM2-ER, ESSM and RAM, while the amphibs will be modeled with RAM alone. The latter decision followed an examination of the hardkill systems currently employed on different classes of amphibs in the USN inventory, revealing many different combinations of missile systems (including none in some cases). Table 5 offers a snapshot of the key values that are fixed for the two-ship scenario.

Formation	Amphib1 (Guide), Amphib2, CG
Formation range from ASCM site	35
ASCM Raid Size	10
ASCM Phit	0.8
SM2-ER Phit	0.5
ESSM Phit	0.6
RAM Phit	0.7
Softkill effectiveness	0.4

Table 5. Fixed values for three-ship scenario.

The ASCM threat continues to be modeled as a supersonic low-flyer with a high Phit of 0.8, but with a fixed salvo size of ten missiles.

2. Variables

For each variation of the standard three-ship scenario, the defensive battle is run five times. The scenario features five primary independent variables that are altered for the purpose of identifying the ship formation orientations that provide the greatest mutual defense benefits. These include the formation of the amphibious ships, the relative bearings of the cruiser and the ASCM site from the formation, the range of the cruiser from the Guide, and the formation missile defense applied in a particular simulation run. Table 6 displays the matrix of variables adjusted for each simulation run. A total of 135 distinct simulations are run for this phase of the study.

Amphibious Ship Formation	Column, Line of Bearing, Line Abreast
Relative Bearing of CG from Guide	180, 225, 270, 315, 360
Range of CG from Guide (nm)	2, 5, 10
Defense employed by CG / Amphibs	- SM2-ER / RAM - ESSM / RAM - RAM / RAM
Rel. Bearing of ASCM site from Formation	180, 225, 270, 315, 360

Table 6. Simulation matrix of variables for multi-ship problem.

a. Amphibious Ship Formation

The formation of the two amphibious ships for any simulation run consists of either a column, a line of bearing, or a line abreast. The range between the two ships is fixed at one nautical mile, and a relative bearing of 135 degrees from the Guide to the second amphib was chosen for the line of bearing.

b. Bearing of ASCM Site From Formation

Within the executable program, the bearing is coded to iterate every 45 degrees from 180R to 360R. For each instance of the ship formation that is simulated, the ASCM site is shifted to a different bearing five times. This has the benefit of more thoroughly testing a particular formation orientation by launching on the formation from different angles, with the expectation that weak spots in the defense will be revealed.

c. Bearing of Cruiser From Guide

The bearing of the cruiser from the Guide is varied every 45 degrees from 180R to 360R for a total of five different formation orientations by bearing.

d. Range of Cruiser From Guide

The range of the cruiser from the Guide is assigned values of 2, 5, and 10 nautical miles. In combination with the changes in bearing, a total of 15 different positions of the cruiser relative to any particular formation are tested.

e. Formation Missile Defense

There are three possible missile defenses modeled on each change to the formation orientation. The first defense that is tested models SM2-ER on the cruiser, and RAM on both amphibs. The second defense models ESSM on the cruiser and RAM on the amphibs. The third defense tests the effectiveness of RAM alone on all ships. The salvo policy in all cases consists of Shoot-Shoot-Look (SSL).

f. Formation Softkill Defense

A softkill effectiveness of 0.4 is applied this time, primarily due to the presence of the two amphibs which offer a far larger radar cross section than the cruiser. One of the weaknesses of the model is that only one value for softkill can be set, and it applies to all ships in the formation. A better method would allow a different value to be assigned to each ship, and when combined with the different RCS values, a greater degree of complexity in the softkill defense battle should be achieved that may mirror reality more closely.

3. Data Collection

Data collection and MOEs for the two-ship scenario simulations mirror the proposals for the single-ship study.

IV. RESULTS

A. DATA RESULTS FOR SINGLE-SHIP PROBLEM

1. Overall Defensive Missile Performance Results

Table 7 details the breakdown for the simulations accomplished in the Single-Ship Problem, specifically, an ASCM site firing on a modeled AEGIS cruiser. Three missile systems were modeled and tested, and the respective firing policies that were utilized are also listed. The same eighty-one scenarios are run for each missile system, and for each firing policy. The model's system limitations, as well as the time demands involved in running a single simulation, made it necessary to limit each scenario to five trials apiece.

Missile System	Firing Policy	Scenarios	Trials/Scenario	Total Trials
SM2	SSL	81	5	405
	SLS	81	5	405
ESSM	SSL	81	5	405
	SLS	81	5	405
	S	81	5	405
RAM	SSL	81	5	405
	S	81	5	405
		567		2835

Table 7. Simulation accomplishment for Single-Ship Problem.

Figure 2 offers an overall snapshot of the performance of each missile system and its respective firing policy. Each trial returns a count of ASCM hits on the cruiser for that single missile exchange, and statistical data is generated following the fifth trial. The graph in Figure 2 displays the total hits by the ASCM across all five trials for each of the eighty-one scenarios, and offers some interesting observations.

Each missile system defends best when in a SSL firing mode, and progressively worsens when SLS and/or S firing policies are employed. This is observed in Figure 2 by the increasing number of ASCM hits on the cruiser when SSL, SLS, and S are respectively applied to each missile system. By inspection, firing policy has a significant effect on the number of ASCM hits received by the cruiser. As in the case of SM2ER, the difference between SSL and SLS is 194 ASCM hits, suggesting a decisive advantage for a SSL policy. This agrees with the firing policy conclusions reached in some of the studies cited in the first chapter of this thesis.

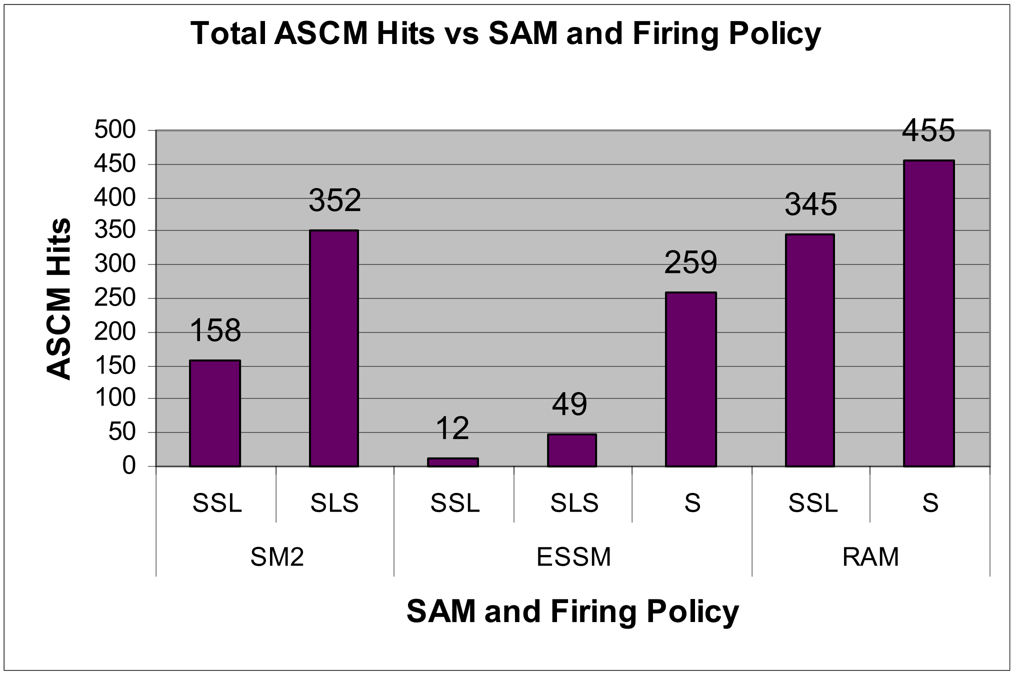

Figure 2. Total counts for ASCM hits versus each SAM and firing policy.

Furthermore, accepting SSL as the optimum firing policy, ESSM demonstrates the greatest effectiveness against the supersonic, low-flying ASCM modeled in this thesis. Over the same eighty-one scenarios or 405 trials, ESSM permits a paltry 12 ASCM hits, while RAM has the worst performance with 345 hits on the cruiser. SM2 falls near the middle with 158 hits inflicted. The performance of RAM is sensible, such as it is, because the missile system is designed for close-in defense out to a maximum of 5 nautical miles (nm). RAM cannot be expected to handle saturation (ie, many and/or closely spaced missiles) well, particularly when faced with a launch delay for fratricide reasons (in this case, four seconds).

Figure 3 displays the success of the defensive missile systems in killing ASCMs, and the data is managed in the same manner as represented in Figure 2. The observations parallel those made for Figure 2, that for each missile system a policy of SSL is superior, and ESSM is the best performer while RAM is the worst.

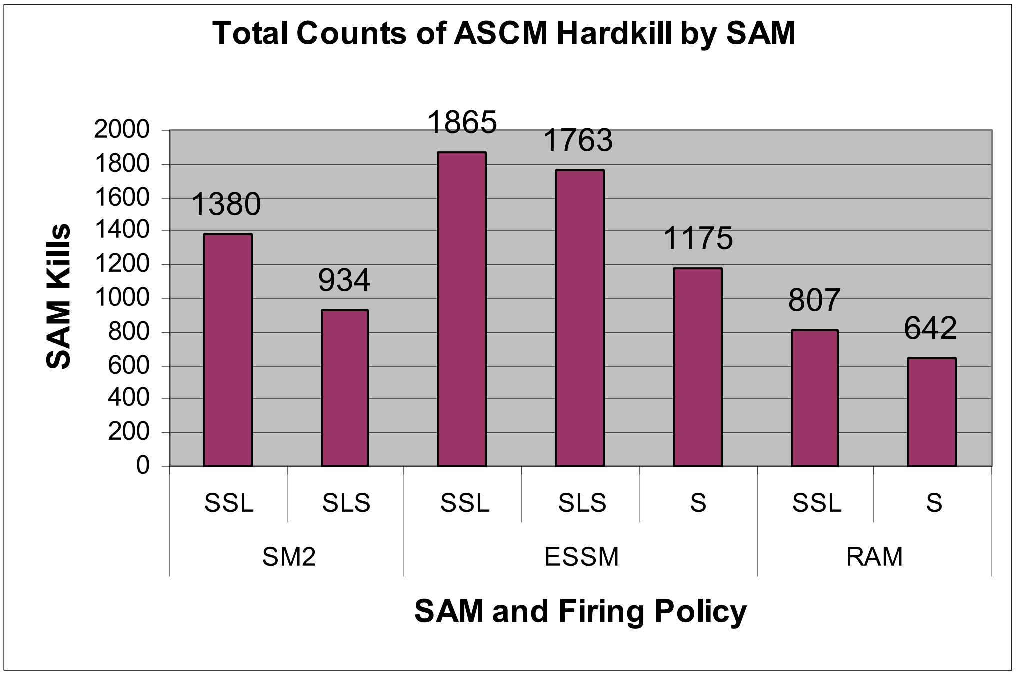

Figure 3. Total counts of ASCM hardkill by each SAM and firing policy.

2. Testing the Effect of Variables on Model Performance

An effort was made to understand the sensitivity of the model following manipulation of some primary variables. Of particular interest are tests of independence regarding the effectiveness of defensive missile systems when examined against different categories of variables.

The data was originally presented in the form of counts or frequencies, and the total counts across each set of 405 trials was organized into contingency tables for categorical data analysis. Tests for independence are conducted with the application of the Chi-square ($\chi2$) test.

a. SAM Hardkill and Range

Tables 8, 9, and 10 contain the observed cell counts for ASCM launch platform range and hardkill by SM2ER, ESSM, and RAM. The hypothesis of interest in each case is that hardkill results for the SAM are independent of range. At a significance level of 0.05 the tabulated $\chi2$ value for 2 degrees of freedom (df) is 5.991.

	15	25	35	
SM2	393	472	515	1380
Softkill	86	75	49	210
Total Kills	479	547	564	1590

Table 8. Observed cell counts for SM2ER hardkill and ASCM launch range (nm).

	15	25	35	
ESSM	624	620	621	1865
Softkill	2	4	3	9
Total Kills	626	624	624	1874

Table 9. Observed cell counts for ESSM hardkill and ASCM launch range (nm).

	15	25	35	
RAM	266	285	256	807
Softkill	181	176	173	530
Total Kills	447	461	429	1337

Table 10. Observed cell counts for RAM hardkill and ASCM launch range (nm).

In the latter two cases, the hypothesis holds true. For ESSM, the calculated value of the test statistic is 0.676 with a p-value of 0.713. RAM data yielded a calculated value of 0.632 with a p-value of 0.729.

SM2ER and range, however, does reject the null hypothesis with a calculated test statistic value of 19.585 and a p-value less than 0.001. The explanation for this divergence probably has to do with the maximum ranges set for each SAM as they relate to the ASCM launch range. With possible ASCM launch ranges of 15, 25, and 35 nm, only SM2ER with a max range of 100 nm has the potential to engage at all distances. The further the ASCM launch, the more engagement opportunities SM2ER will have. In the case of ESSM and RAM, their max ranges are respectively 16 nm and 5 nm, so both missile systems are forced to wait until the ASCM enters their respective engagement zones.

Another factor possibly confounding any advantages that may arise out of the range from the formation of an ASCM launch site is the manner in which detection is handled by the ASMD model. As the code is currently written, detection and tracking by sensors are perfect. However, real world ASCM threats, present and future, are typically characterized by some degree of stealth. Stealth can be conferred by a low flight profile, high speeds and maneuver that challenge the tracking radar, environmental conditions, or by passive and active countermeasures. All of these characteristics impact the Signal Target Threshold (STS), the point at which a ship's radar return is strong enough for track and engagement of the ASCM to proceed. Typically, STS occurs at or near the radar horizon, perhaps closer to the ship, depending on the threat. As an example, a ship's radar may detect a target from as far away as fifty nautical miles, but may not receive sufficient radar return for tracking and illumination until twenty nautical miles. This is why ships generally consummate engagements within the radar horizon. It goes without saying that STS can have a deleterious effect on the Detect-to-Engage (DTE) sequence.

Townsend's ASMD model establishes several limits on the functionality of sensors. There is a maximum range for target detection, a maximum detection rate, and a maximum number of targets that can be tracked at any one time. (Townsend, 1999) At the moment, there is no method for collecting sensor data to determine when detection occurs. With that in mind, if the user models his sensors with the above parameters following real world values, his detection and track characteristics can be predicted to greatly exceed expectations.

In addition to the effects of simple sensors, Townsend chose not to include features concerning target aspect and radar cross section of the threat since the additional complexity wasn't relevant to the problem he was investigating (Townsend email of October 1, 2000). It becomes arguable, though, that to gain insight into defense against small-scale missile attacks, a ship's sensors necessarily require a significant stressor to inject realism into the simulation.

b. SAM Hardkill and ASCM Raid Size

Tables 11, 12, and 13 contain the observed cell counts for ASCM raid size and hardkill by SM2ER, ESSM, and RAM. The hypothesis of interest in each case is that hardkill results for the SAM are independent of ASCM raid size. At a significance level of 0.05 the tabulated $\chi 2$ value for 2 df is 5.991.

	2	4	8	
SM2	214	427	739	1380
Softkill	21	40	149	210
Total Kills	235	467	888	1590

Table 11. Observed cell counts for SM2ER hardkill and ASCM raid size.

	2	4	8	
ESSM	269	534	1062	1865
Softkill	0	2	7	9
Total Kills	269	536	1069	1874

Table 12. Observed cell counts for ESSM hardkill and ASCM raid size.

	2	4	8	
RAM	115	204	488	807
Softkill	96	148	286	530
Total Kills	211	352	774	1337

Table 13. Observed cell counts for RAM hardkill and ASCM raid size.

In the case of SM2ER and RAM, the null hypothesis is rejected, suggesting that ASCM raid size did affect the hardkill results. For ESSM, the calculated value of the test statistic is 2.108 with a p-value of 0.348, supporting the null hypothesis.

SM2ER data reports a calculated test statistic value of 22.402 and a p-value less than 0.001. RAM data yielded a calculated value of 6.216 with a p-value of 0.045. As shown in Figure 3, ESSM performs exceptionally well against the modeled ASCM, while SM2ER and RAM enjoy far less success in comparison. Each modeled SAM is fairly distinct from the others in terms of P(Hit) values, max range, speed, launch cycle times, and launcher capacity (40 SM2ER and ESSM in the VLS, 11 RAM) . The manner in which these variables have come together and provided such an effective result for ESSM has significantly weakened any advantage normally attributed to a large ASCM raid size. This model behavior in the case of ESSM will be explained later. SM2ER and RAM are not so effective that large raid sizes can be engaged as effectively as small raid sizes. This is a reasonable expectation from a real-world point of view, that larger raid sizes increase the likelihood a leaker will penetrate and hit the ship.

c. *ASCM Hits and ASCM Raid Size*

Examining the effects of raid size on ASCM hits yields some interesting insights. Tables 14, 15, and 16 contain the observed cell counts for ASCM hits and ASCM raid size against each missile defense system. The hypothesis of interest in each case is that ASCM hits are occurring independent of ASCM raid size. At a significance level of 0.05 the tabulated $\chi 2$ value for 2 df is 5.991.

	2	4	8	
SM2	17	37	104	158
Softkill	21	40	149	210
Total Kills	38	77	253	368

Table 14. Observed cell counts for ASCM hits and ASCM raid size vs an SM2ER defense.

	2	4	8	
ESSM	1	4	34	39
Softkill	0	2	7	9
Total Kills	1	6	41	48

Table 15. Observed cell counts for ASCM hits and ASCM raid size vs an ESSM defense.

	2	4	8	
RAM	34	119	192	345
Softkill	96	148	286	530
Total Kills	130	267	478	875

Table 16. Observed cell counts for ASCM hits and ASCM raid size vs an RAM defense.

The null hypothesis is not rejected for the data provided in Tables 14 and 15, suggesting that ASCM hits occur independently of ASCM raid size when SM2ER or ESSM are defending the ship. ASCM hits data versus SM2ER reports a calculated test statistic value of 1.218 and a p-value equal to 0.544. ESSM data yielded a calculated value of 1.144 with a p-value of 0.564. The null hypothesis is rejected in the case of ASCM hits versus RAM defense, with a test statistic equal to 12.656 and a p-value of 0.002. This result likely reflects the 5 nm engagement zone and fratricide delay for RAM, which can easily lead to saturation of the defense by large ASCM raid sizes. Again, RAM is expected to handle limited ASCM raid sizes or a small number of leakers.

d. SAM Hardkill and SAM P(Hit) Values

Table 17 contains the observed cell counts for SAM hardkill and P(Hit) values that respectively apply to SM2ER, ESSM, and RAM. The hypothesis of interest in each case is that hardkill results for the SAM are independent of assigned P(Hit) for the defensive missile systems. At a significance level of 0.05 the tabulated $\chi 2$ value for 2 df is 5.991.

	0.5	0.6	0.7	
Hardkill	1380	1865	807	4052
Softkill	210	9	530	749
Total Kills	1590	1874	1337	4801

Table 17. Observed cell counts for hardkill by SAMs and SAM P(Hit) values.

The analysis result definitively rejects the null hypothesis which states that P(Hit) values do not influence hardkill results for a SAM. A test statistic of 919.155 provides a p-value equal to zero.

Probability-of-hit values exert a significant measure of control over the performance of modeled defensive missile systems, but certainly are not the sole determinant. The manner in which the model handles an engagement mirrors fairly closely a real-world engagement. The ship's sensors detect and track the threat missile, then a surface-to-air missile is launched and guided all the way to intercept. Proper kinematics are applied to missile flight within the model. Whether a kill occurs at intercept or not is finally determined by the P(Hit) value.

Figure 4 illustrates well the non-primary role of P(Hit) values in the final hardkill counts. Though RAM is expected to be the most lethal missile with a P(Hit) equal to 0.7, its ASCM hardkill counts pale in comparison to SM2ER and ESSM. This demonstrates a certain level of complexity within the model when it comes to resolving a missile exchange. RAM's lethality is handicapped to a greater extent than SM2ER and ESSM by range restrictions, perhaps speed, and launch delay due to fratricide. SM2ER makes up for its P(Hit) weakness with a greater engagement range and faster subsequent launches out of the MK41 VLS.

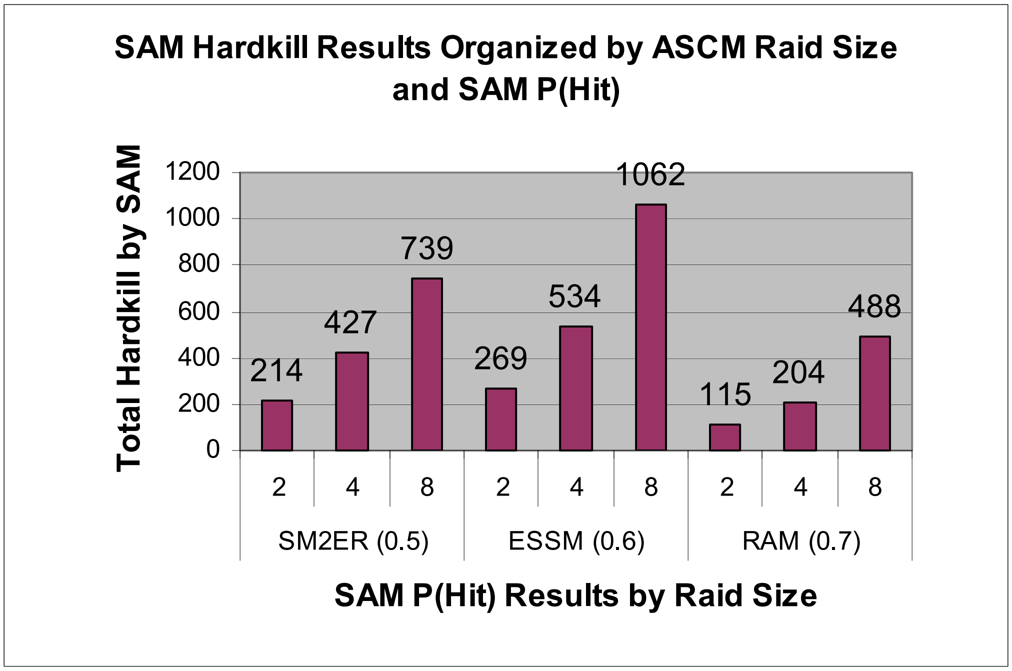

Figure 4. SAM hardkill results when organized by ASCM raid size and SAM P(hit).

e. SAM Hardkill and SAM Launch Cycle Times

Tables 18 and 19 contain the observed cell counts for SAM hardkill and launch cycle times (sec) that respectively apply to SM2ER and RAM, and ESSM and RAM. The hypothesis of interest in both cases is that hardkill results for SAMs are independent of how quickly the subsequent missiles leave the launcher. At a significance level of 0.05 the tabulated $\chi 2$ value for 2 df is 5.991.

	1 (SM2ER)	4 (RAM)	
Hardkill	1380	807	2187
Softkill	210	530	740
Total Kills	1590	1337	2927

Table 18. Observed cell counts for SAM hardkill and launch cycle time (sec) (SM2ER and RAM).

	1 (ESSM)	4 (RAM)	
Hardkill	1865	807	2672
Softkill	9	530	539
Total Kills	1874	1337	3211

Table 19. Observed cell counts for SAM hardkill and launch cycle time (sec) (ESSM and RAM).

In both cases the null hypothesis is rejected in favor of the statement that launch cycle times do indeed affect hardkill results. The comparison between SM2ER and RAM yielded a test statistic equal to 268.645 and a p-value of zero. The comparison between ESSM and RAM validates the former with a test statistic of 856.678 and p-value equal to zero.

f. SAM Hardkill and SAM Speeds

Tables 20 and 21 contain the observed cell counts for SAM hardkill and speed (Mach) that respectively apply to SM2ER and ESSM, and RAM and ESSM. The hypothesis of interest in both cases is that hardkill results for SAMs are independent of the speed of the defensive missile itself. At a significance level of 0.05 the tabulated $\chi 2$ value for 2 df is 5.991.

	2.5 (SM2ER)	5.0 (ESSM)	
Hardkill	1380	1865	3245
Softkill	210	9	219
Total Kills	1590	1874	3464

Table 20. Observed cell counts for SAM hardkill and speed (Mach) (SM2ER and ESSM).

	2.5 (RAM)	5.0 (ESSM)	
Hardkill	807	1865	2672
Softkill	530	9	539
Total Kills	1337	1874	3211

Table 21. Observed cell counts for SAM hardkill and speed (Mach) (RAM and ESSM).

Analysis of the data in both cases leads to rejection of the null hypothesis, suggesting that missile speed does affect hardkill results. The comparison between SM2ER and ESSM yielded a test statistic equal to 235.265 and a p-value of zero. The comparison between RAM and ESSM validates the former with a test statistic of 856.678 and p-value equal to zero.

3. Pertinent Points Regarding Model Performance with Respect to the Single Ship Problem

In looking at the Single Ship problem, the objective was to gain understanding of the ASMD model's behavior by seeking to answer questions regarding the employment of planned defensive missile systems. The future missile systems of interest are ESSM and a new variant of RAM, both of which appear to have performed as expected relative to SM2ER in terms of hardkill effectiveness. To that end, the model has demonstrated a future potential for conducting quick assessments on new or proposed missile systems.

Variables to which the model demonstrated sensitivity includes missile speed, missile P(hit) values, and the time delay between missile launches on the defensive side. Some sensitivity was also shown in the case of ASCM raid sizes, which is a good result because saturation can occur to even the best defense.

Sensor detection by the ship is conveyed a sizable advantage due to the manner it was modeled as discussed earlier. Though it can be overcome, this does have the effect of tilting the playing field in favor of the ship, and will require the user to model his systems and characteristics carefully to ensure a satisfactory result from the missile exchange.

B. DATA RESULTS FOR THE MULTI-SHIP PROBLEM

1. Overall Defensive Performance Results by Multi-Ship Formation

Table 22 describes the simulation accomplishments for this portion of the study, specifically, an ASCM site firing on a modeled formation consisting of one AEGIS cruiser and two generically designed amphibious-class ships. Three missile system combinations were modeled and tested, and in all cases a firing policy of SSL was applied. This is due to the ASMD model limitation of one firing policy that can be utilized for all missile systems, as well as the superior performance of a SSL policy demonstrated in the single-ship portion of this study.

Fifteen scenarios were run on the two amphibs alone to demonstrate their vulnerability when defending with RAM alone, the concept of which is illustrated in Figure 5. For the three-ship composition, as depicted in Figure 6, three different defenses are applied. For each defense measure, RAM is employed by the amphibs while the cruiser tests SM2ER, ESSM, and RAM. The same forty-five scenarios are run for each formation defensive measure. The model's system limitations, as well as the time demands involved in running a three-ship simulation, made it necessary to limit each scenario to five trials apiece.

Formation Composition	Formation Defense	Scenarios	Trials/Scenario	Total Trials
2 Amphibs	RAM	15	10	150
1 CG	SM2ER	45	5	225
2 Amphibs	RAM			
1 CG	ESSM	45	5	225
2 Amphibs	RAM			
1 CG	RAM	45	5	225
2 Amphibs	RAM			
		150		825

Table 22. Simulation accomplishment for Multi-Ship Problem.

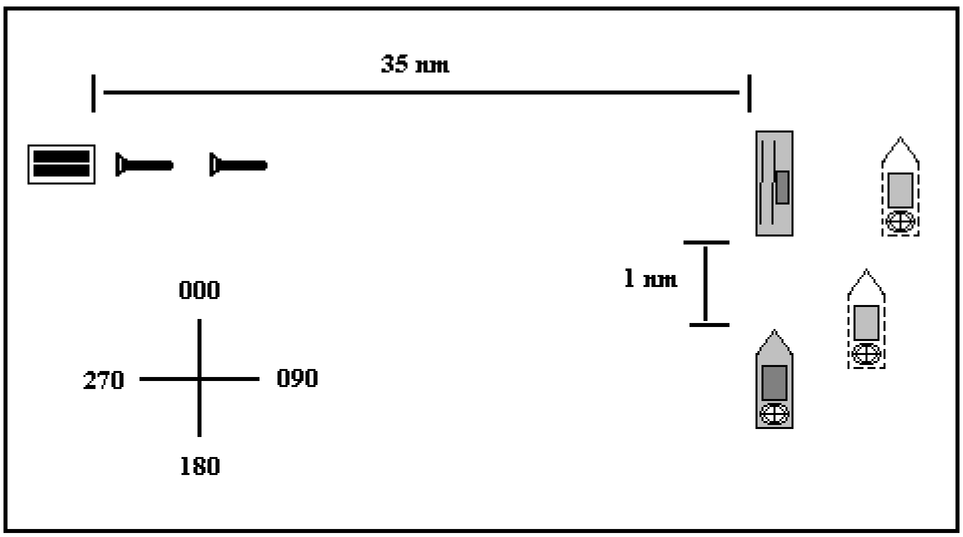

Figure 5. An illustration of an ASCM attack on two amphibs in: a column, line of bearing (135R), and line abreast formations.

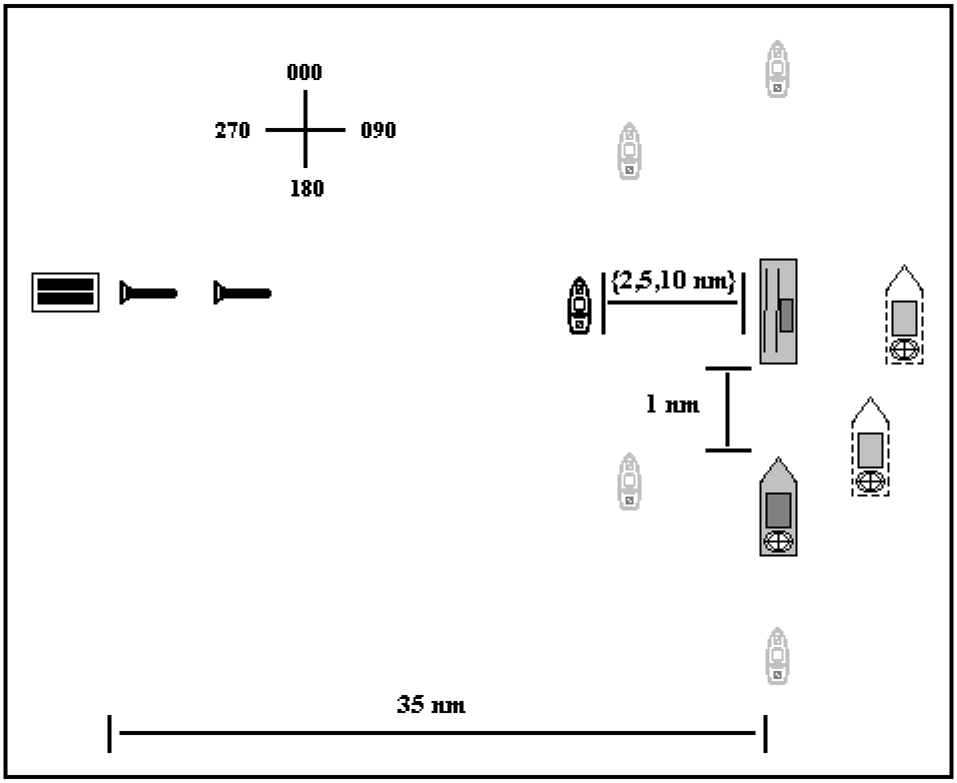

Figure 6. An illustration of the various dispositions employed by a multi-ship formation against each ASCM attack.

Figure 7 offers a graph of the mean ASCM hits sustained by each amphib while operating without the support of a cruiser. The sole defenses against an ASCM salvo of size 10 are RAM systems with a P(Hit) equivalent to 0.7, a softkill capability of 0.4, and the formation orientation. Although a line of bearing formation appears to offer marginal improvement over the other two formations, each amphib can still expect an average of one hit for each missile exchange, or trial.

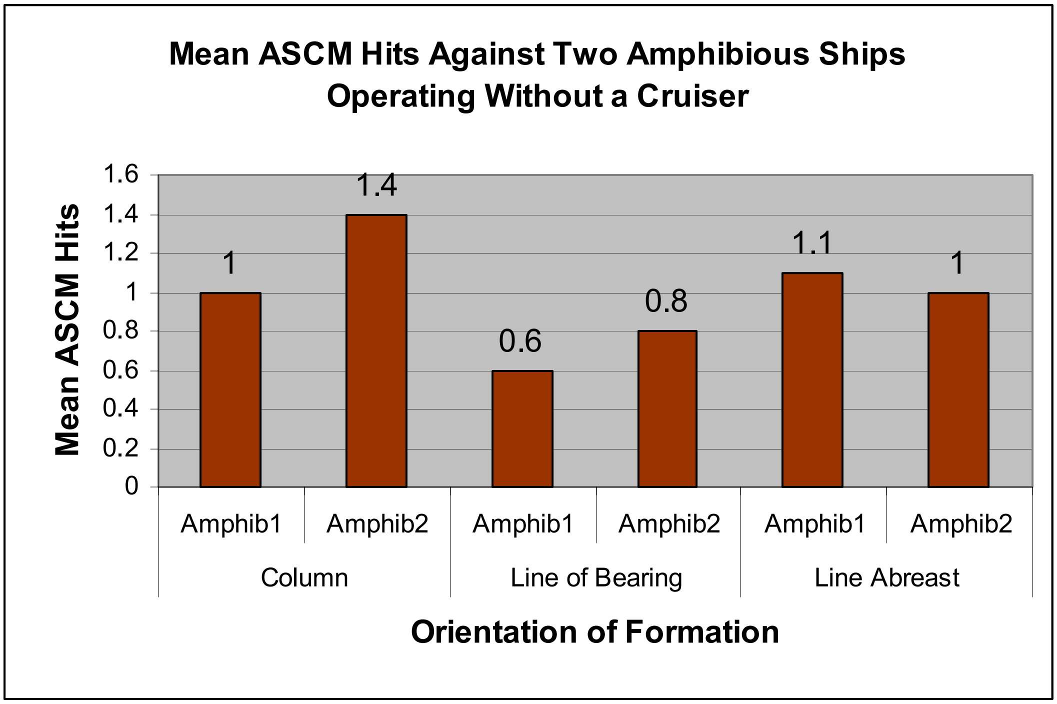

Figure 7. Mean ASCM hits against different orientations of amphibious ship formations operating without a cruiser.

Figure 8 offers an example of the improvements that a cruiser can provide to defense within the context of the ASMD model. Selecting from the data in which the cruiser employs SM2ER and bears 270R and 2 nm from the Guide, both amphibs escape each missile exchange virtually unscathed.

Within the context of the three-ship component of the study, a broad examination of the effects of formation orientation and cruiser bearing and range from the Guide demonstrates little impact is had.

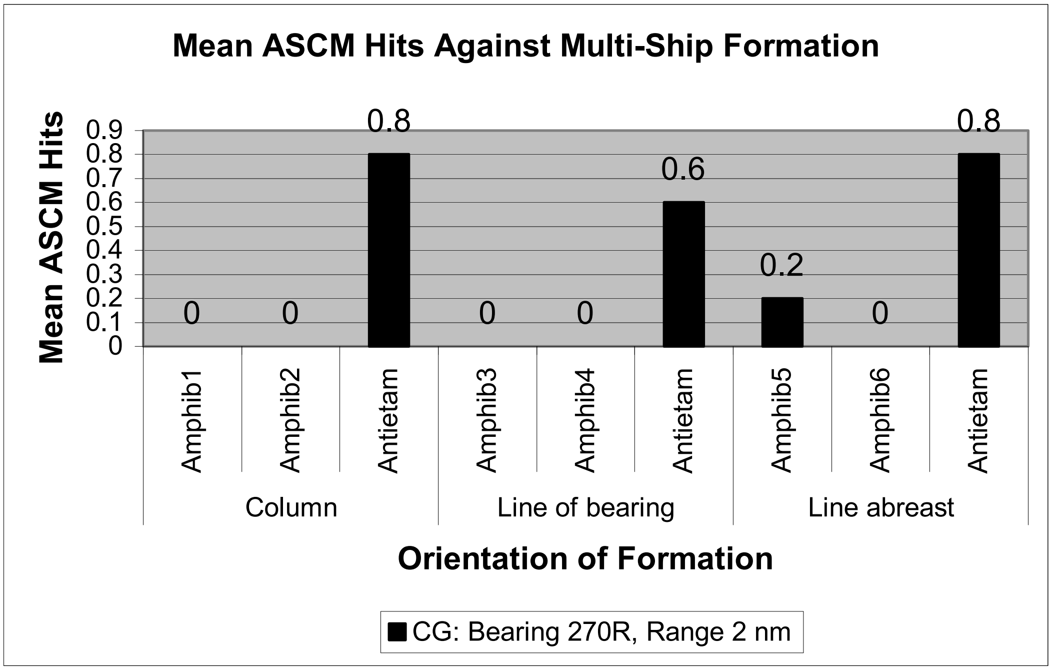

Figure 8. Mean ASCM hits against different orientations of multi-ship formation with cruiser bearing 270 Relative, range 2 nm, from the Guide.

Figure 9 organizes the collection of data regarding the scenarios in which a cruiser and two amphibs are operating in mutual support. Over the course of 675 trials, the total count of ASCM hits that are absorbed by the formation are organized by the type of formation employed and the defensive SAMs respectively employed by the cruiser and amphibs. By inspection, there is no significant relationship between formation and the number of hits received by the ships. The application of the Chi-Square test yields a similar result. At a significance level of 0.05 the tabulated $\chi 2$ value for 4 df is 9.488. The calculated test statistic for this data is equal to 3.689 with a p-value of 0.450.

A similar result is obtained when considering the effects of a cruiser's bearing from the Guide on the total number of ASCM hits sustained. Figure 10 illustrates this data, and an inspection of the graph yields the same conclusion as a Chi-Square test. At a significance level of 0.05 the tabulated $\chi 2$ value for 8 df is 15.507. The value of the calculated test statistic is 7.950 with a p-value of 0.438.

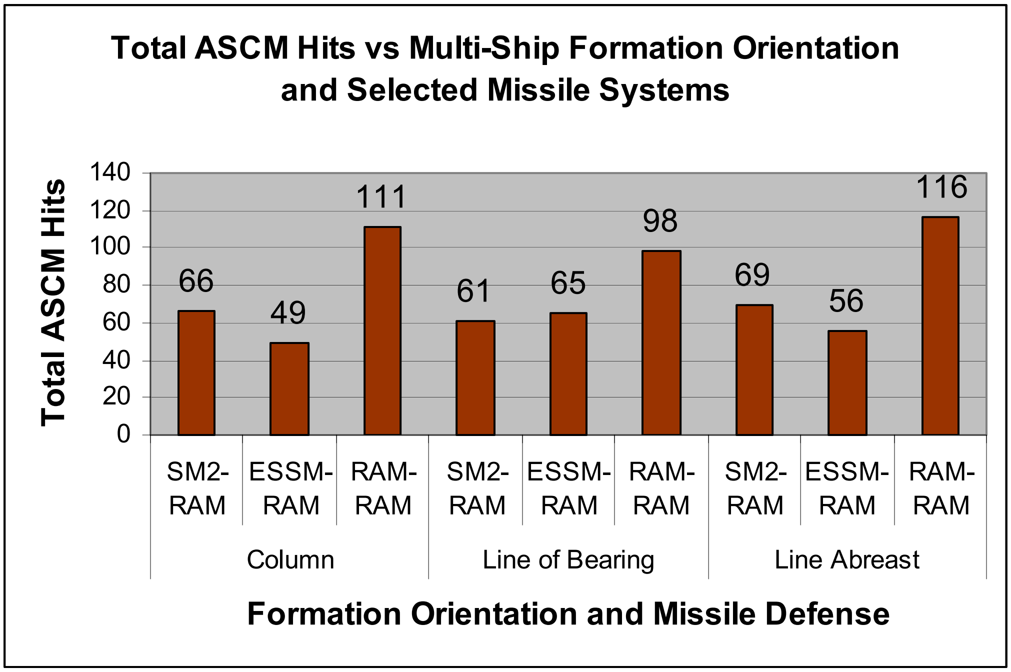

Figure 9. Total ASCM hits vs formation orientation and missile defense.

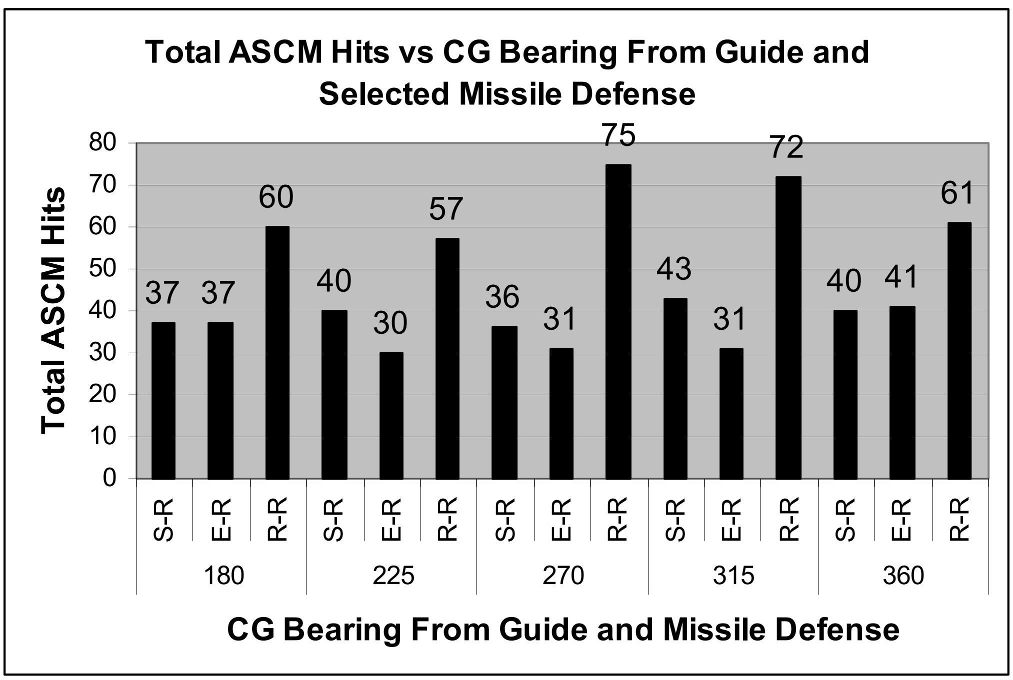

Figure 10. Total ASCM hits vs cruiser bearing from the Guide and missile defense.

The third variable to be tested is the range of the cruiser from the Guide, and is illustrated in Figure 11. The data representing the employment of SM2ER-RAM and

ESSM-RAM shows a consistent decrease in the number of hits incurred by the formation as the cruiser's range decreases. This result likely occurs due to the increased time and range over which to consummate engagements with SM2ER and ESSM, and is probably an ideal tactic to employ against a supersonic ASCM. The closer the cruiser is to the amphibs, the better positioned it will be to intercept the threat. The RAM-RAM data, representing employment of RAM by both the cruiser and amphibs, does not follow the same effect, most likely due to the limitations imposed by range and launch cycle time that were discussed in the single-ship portion of the study.

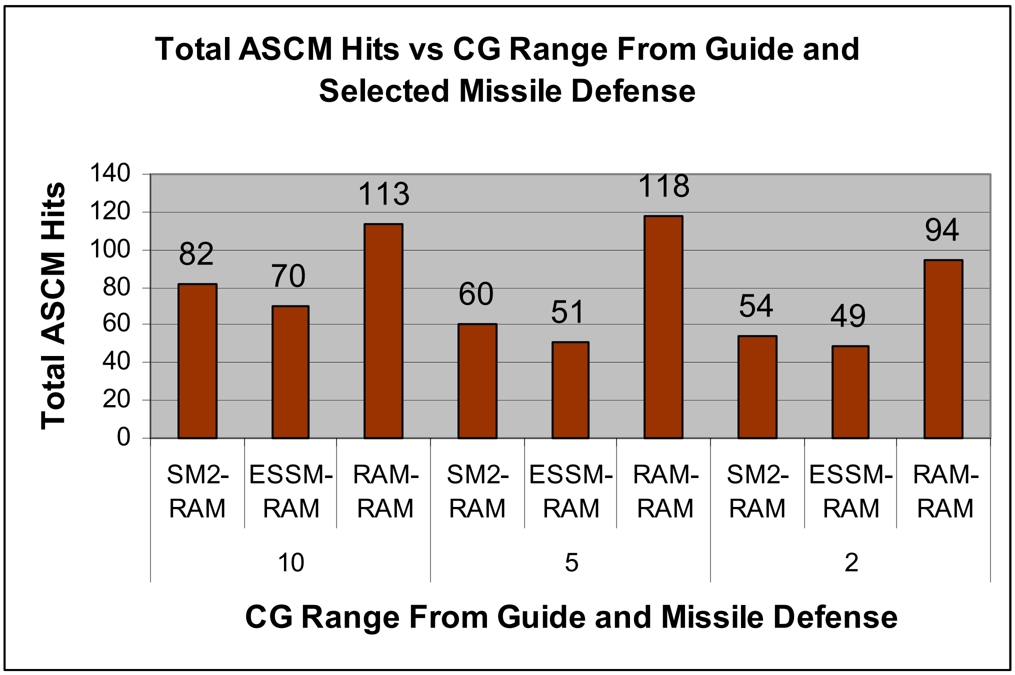

Figure 11. Total ASCM hits vs cruiser range from the Guide and missile defense.

Application of a Chi-Square test to the question of cruiser range effects on sustained ASCM hits suggests the ships are collecting hits independent of the range of the cruiser from the Guide. At a significance level of 0.05 the tabulated $\chi 2$ value for 4 df is 9.488. The calculated test statistic for this data is equal to 4.018 with a p-value of 0.404.

2. An Examination of Smaller Subsets of Simulation Data

a. Formation Orientation

Having looked at the data from a macro perspective in the previous section, it becomes appropriate to more narrowly approach the data collected from the multi-ship simulations. Initially, an examination of the effects of formation orientation on ASCM hits within each one of three formational SAM employments, namely SM2ER-RAM, ESSM-RAM, and RAM-RAM. This data is represented in Figures 12, 13, and 14.

Figure 12 displays the data for a multi-ship formation armed with SM2ER-RAM and testing the effectiveness of a column, line of bearing, and line abreast formations against the supersonic low-flyer. However, a visual examination of the graph reveals that a formation defending with SM2ER-RAM can find no additional advantage in the orientation of the two amphibs.

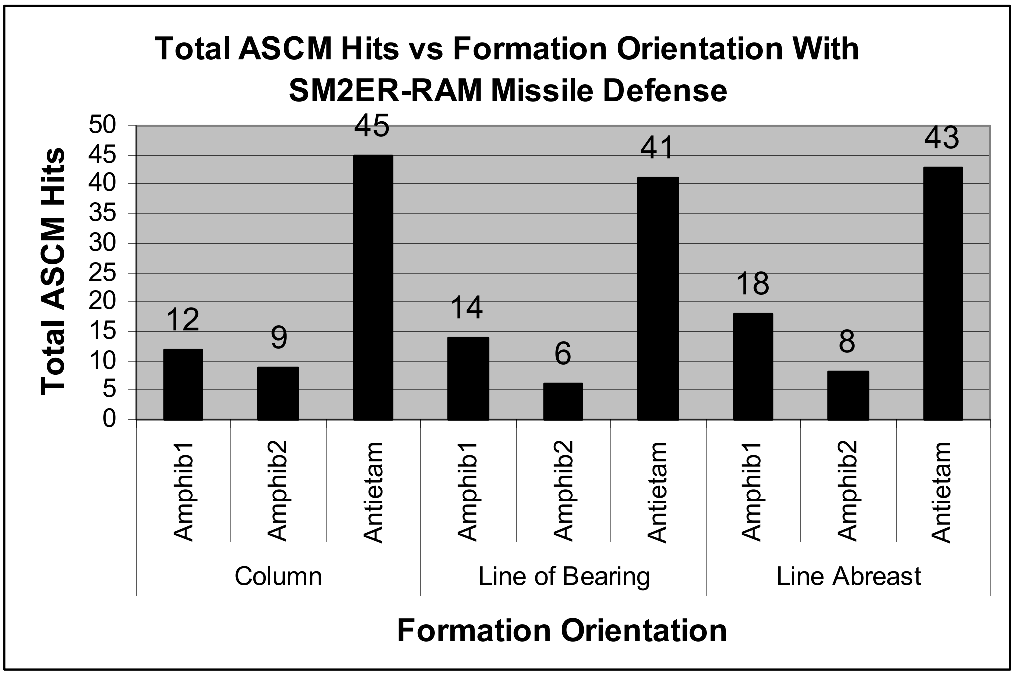

Figure 12. Total ASCM hits vs formation orientation and an SM2ER-RAM defense.

Figure 13 exhibits the data for a multi-ship formation armed with ESSM-RAM and likewise testing the effectiveness of a column, line of bearing, and line abreast formations against the threat ASCM. A visual inspection of the graph shows formation orientation poses little advantage to the amphibs, but reveals marked improvements for the cruiser. Placing the amphibs in a column formation when the cruiser shoots ESSM appears to minimize hits on the cruiser, while a line abreast is second best.

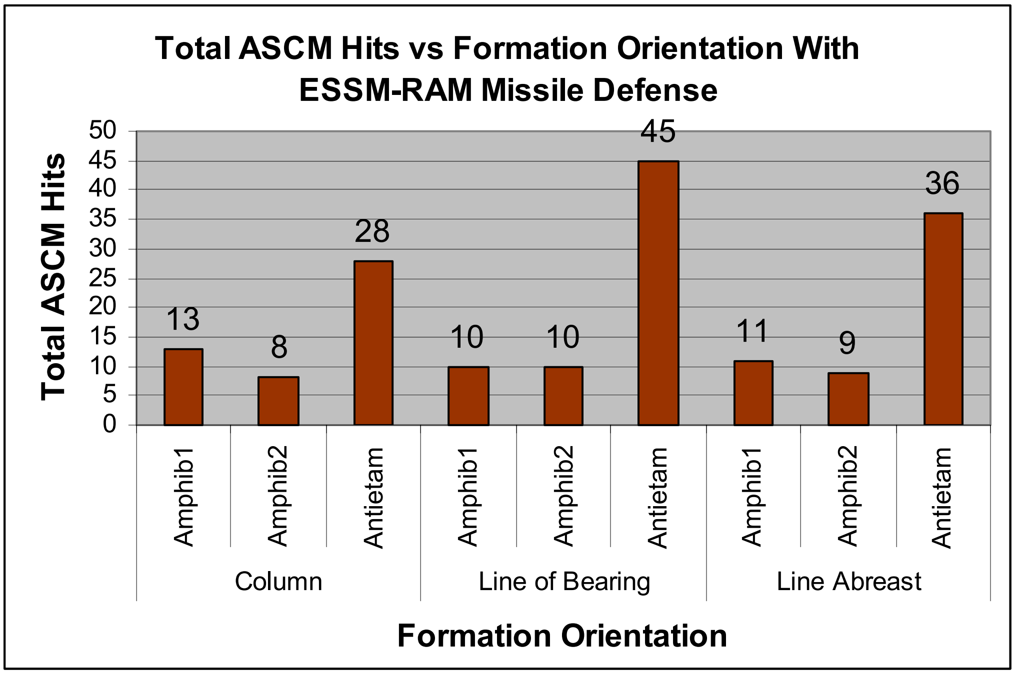

Figure 13. Total ASCM hits vs formation orientation and an ESSM-RAM defense.

Far different observations are to be had according to the data displayed in Figure 14. Clearly, while ESSM edges SM2ER as the most effective SAM to employ against a saturation attack, RAM is the worst performer. Again, this is largely due to RAM's inherent weaknesses as was previously discussed in the single-ship results. No real advantage is to be had for the cruiser or amphibs when the latter are placed in a column formation.

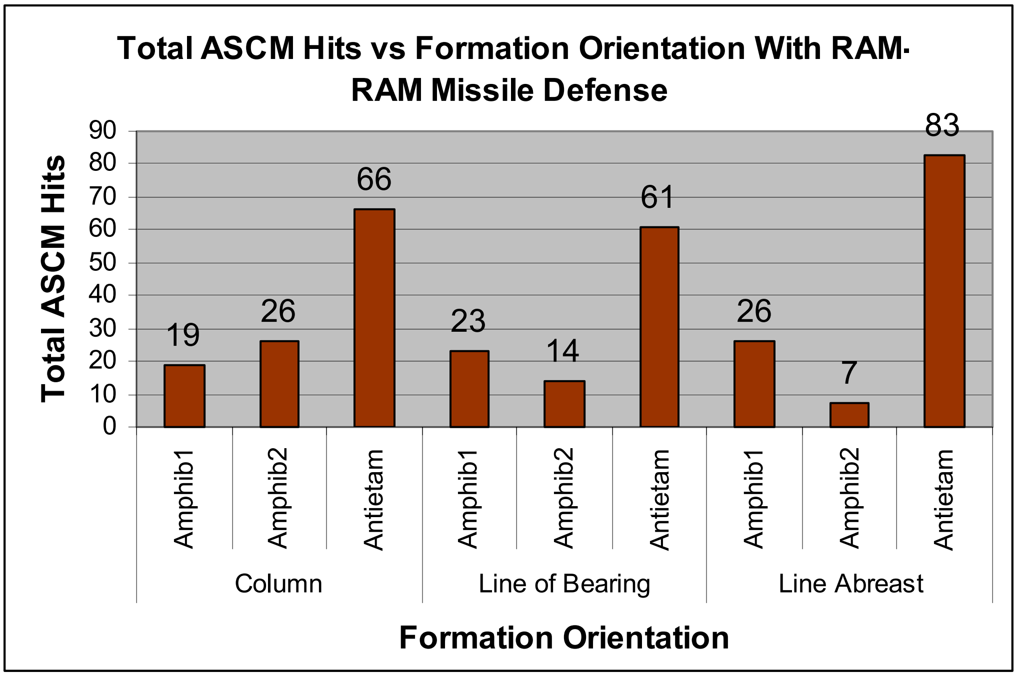

Figure 14. Total ASCM hits vs formation orientation and a RAM-RAM defense.

b. Cruiser Bearing Relative to the Guide

When the data is organized to check the effects of the cruiser's bearing relative to the Guide, the graphs appear to offer some interesting results. Figure 15 displays the data for the set of scenarios in which the cruiser and amphibs are respectively armed with SM2ER and RAM.

As the dominant air warfare platform, the burden of defense truly falls on the cruiser to ensure the two high value units are safely escorted past the ASCM site. Figure 15 strongly suggests that the amphibs receive the greatest measure of protection when the cruiser's relative bearing from the Guide is close to the threat axis of 270R. Of the five relative bearings tested, 225R, 270R, and 315R all demonstrated that effective protection was being extended to the amphibs. This is an excellent outcome to be generated by the ASMD model because it shows the model behaving in a manner consistent with real-world expectations. These expectations include the consideration that a SAM shooter has greater engagement opportunities if he is firing downrange (threat missile coming directly at SAM shooter, features greater intercept ranges) rather than getting involved in crossrange (attempting to intercept threat missile at closest point of approach) or backrange (SAM fired in situation where it must chase the threat missile) scenarios. This result, however, comes at a high cost for the cruiser, having received 35, 34, and 41 hits respectively over 225 simulation trials.

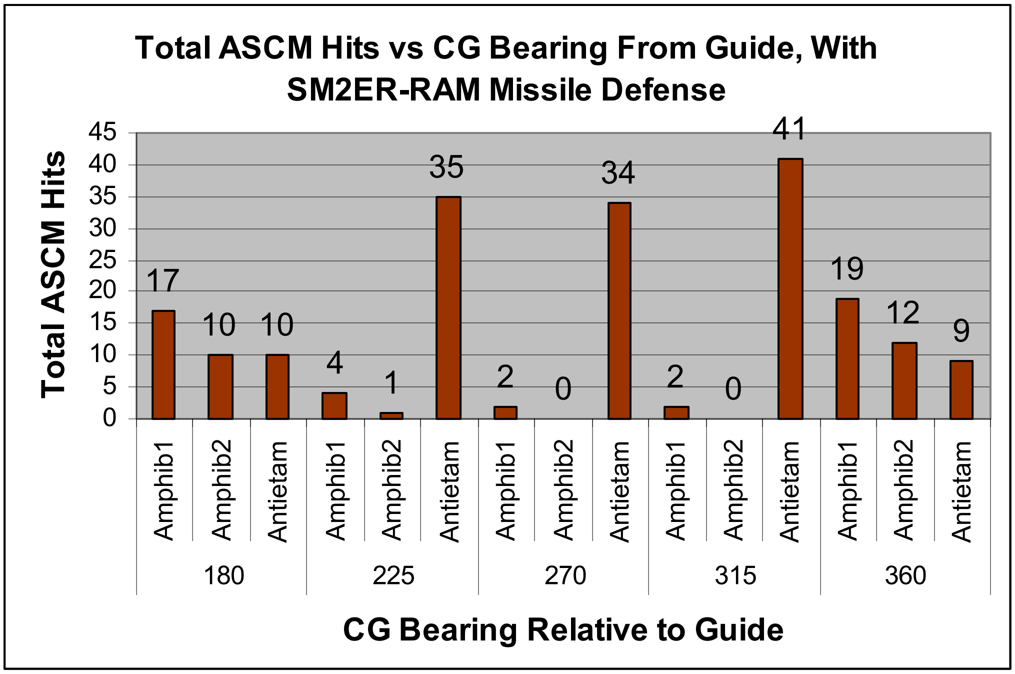

Figure 15. Total ASCM hits vs CG bearing relative to Guide and an SM2ER-RAM defense.

Figure 15 further illustrates that when the cruiser is at a relative bearing furthest from the threat axis, the bulk of the ASCM hits is shifted to the amphibs. This supports the reasonable expectation that when a missile is presented with three radar cross sections (RCS) in a column, it will choose at a larger frequency the target with the greatest RCS.

Figures 16 and 17 are the graphical representations for the data collected from the remaining two sets of scenarios concerned with a cruiser's relative bearing from the Guide. Figure 16 covers the set of 45 scenarios during which the cruiser and amphibs are armed with ESSM and RAM respectively, and Figure 17 for the employment of RAM by all three ships against the threat. Though the ASCM hit counts are different, the results faithfully follow the trends noted above in the case of SM2ER and RAM, and require no further discussion.

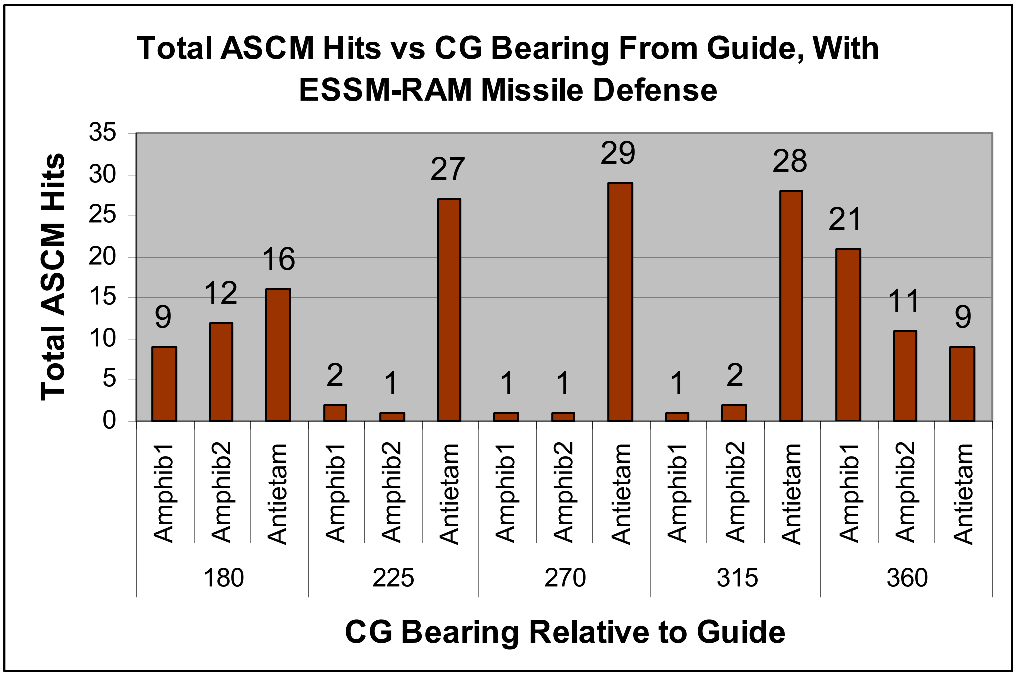

Figure 16. Total ASCM hits vs CG bearing relative to Guide and an ESSM-RAM defense.

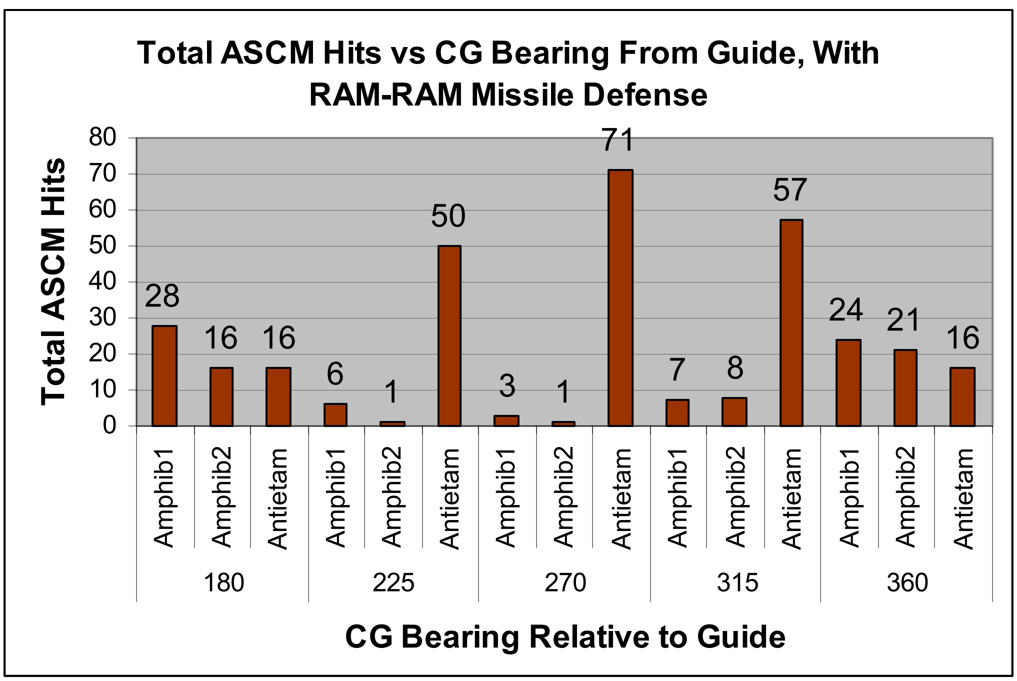

Figure 17. Total ASCM hits vs CG bearing relative to Guide and a RAM-RAM defense.

c. *Cruiser Range Relative to the Guide*

When the data is organized to check the effects of the cruiser's range from the Guide, some consistency can be observed in the results. Figure 18 displays the data for the set of scenarios in which the cruiser and amphibs are respectively armed with SM2ER and RAM. Figure 19 describes the data for the formation's employment of ESSM and RAM, and Figure 20 is employment of RAM by all units.

Figures 18 and 19 suggest that when the cruiser's range from the Guide decreases from 10 to 2 nautical miles, modest and consistent improvement is had for the self-defense of the cruiser. This observation is not the case when the cruiser shoots RAM, as evidenced in Figure 20.

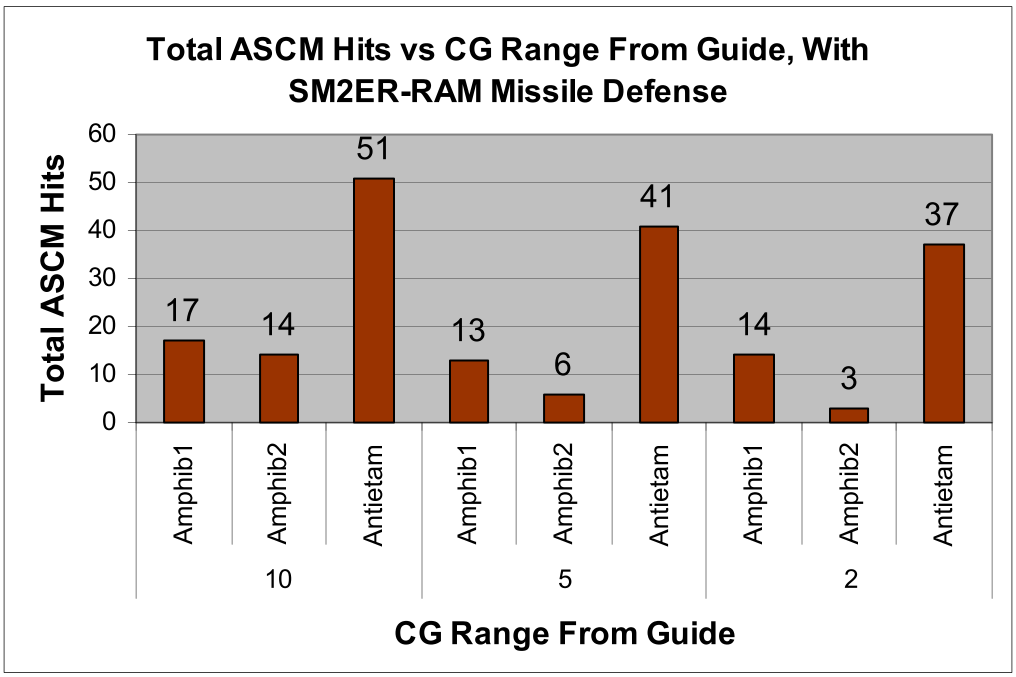

Figure 18. Total ASCM hits vs CG range from Guide and an SM2ER-RAM defense.

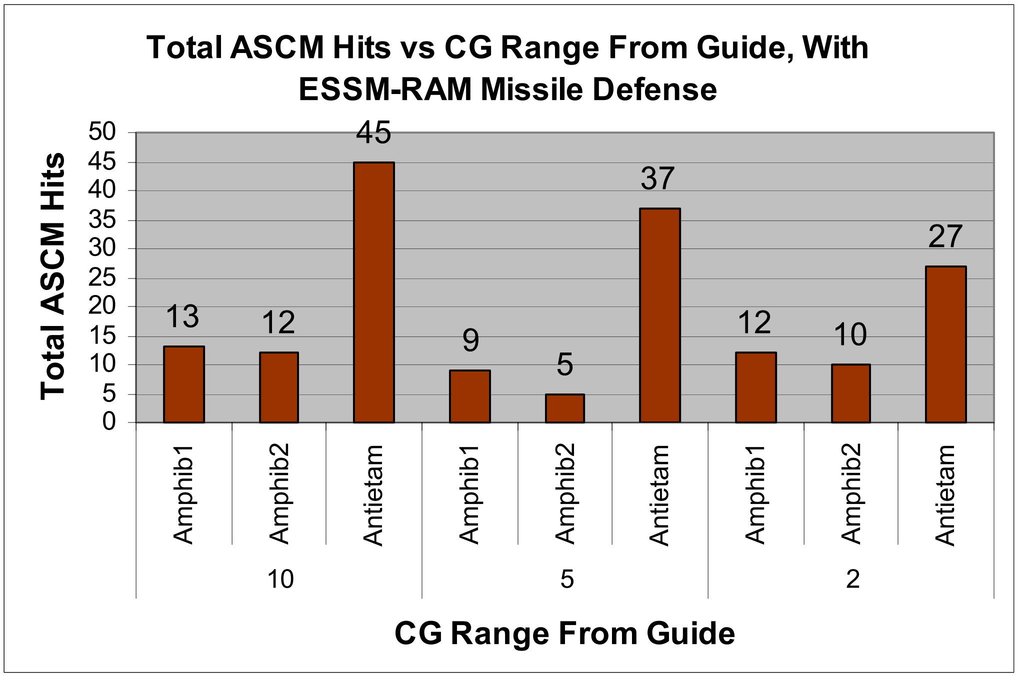

Figure 19. Total ASCM hits vs CG range from Guide and an ESSM-RAM defense.

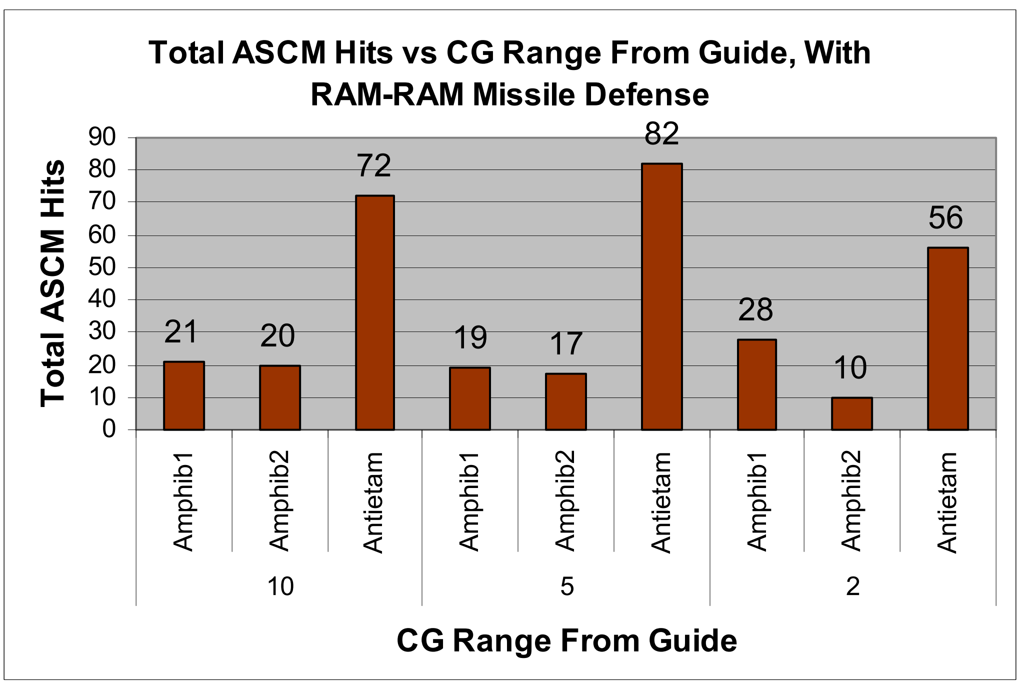

Figure 20. Total ASCM hits vs CG range from Guide and a RAM-RAM defense.

Despite the modest benefit had by the cruiser when stationed 2 nm away from the Guide, there is no significant evidence that mutual support is improved or exists at all, as was the case when the cruiser's relative bearing from the Guide was discussed. In all three cases, the ASCM hits sustained by both amphibs are fairly unchanged from any range. This is a poor result by the ASMD model, because the purpose of placing a SAM shooter in a shotgun position relative to one or more high value units is to significantly attrite the number of inbound threat missiles. This has the added effect of reducing the number of hits on the protected unit or units, a crucial outcome that is not happening in the context of range from Guide.

d. Specific Cases Where Successful Defense Can Be Noted

A total of 225 scenarios were run in support of the three-ship defense concept, and for each scenario there are five trials. Fifty-five of the scenarios resulted in zero hits on the high value units, or amphibs in this case. In virtually all of these 55 cases, the cruiser suffered at least one hit, and only once did the cruiser receive no hits across five trials. Figure 21 is a graphical display of the number of ASCM hits absorbed by the cruiser across five trials for each of the 55 scenarios in which both amphibs received no hits.

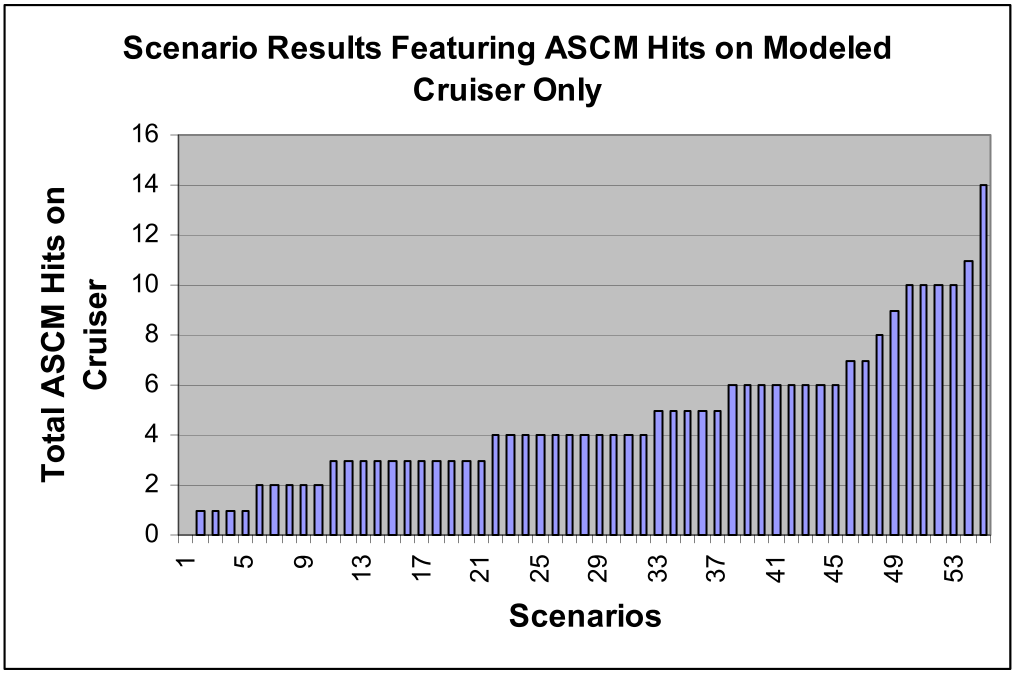

Figure 21. Total ASCM hits on the cruiser in all scenarios in which both amphibs received no hits.

Though the tactical commander is concerned mightily with the defense of the high value units, he obviously wants to mitigate ASCM hits on the SAM shooter. In support of that goal, it is appropriate to focus on the left side of Figure 21.

Table 23 captures the data that represents the fewest ASCM hits on the cruiser while the amphibs remain hitless. Though none of the three amphibious formations shows up as a clear favorite, column and line abreast do appear to offer the most success for zero hits or a single hit. In the case of the cruiser's relative bearing from the Guide, one clearly cannot go wrong with positioning at 225R or 315R from the Guide, while 270R is not as strong, and 180R and 360R are ill-advised. Cruiser range from the Guide works well at 2 or 5 nm, and employment of ESSM appears to offer the greatest likelihood for ASCM attrition.

	Formation	CG Bearing	CG Range	CG SAM
0 Hits	Column	225R	5	ESSM
1 Hit	Column	315R	2	SM2ER
	Column	225R	2	ESSM
	Line Abreast	315R	5	ESSM
	Line Abreast	315R	2	ESSM
2 Hits	Line of Bearing	315R	5	SM2ER
	Line of Bearing	225R	5	ESSM
	Line of Bearing	225R	2	ESSM
	Line Abreast	270R	10	ESSM
	Line Abreast	270R	2	ESSM

Table 23. Summary of data representing the fewest ASCM hits on the cruiser.

3. Pertinent Points Regarding Model Performance with Respect to the Multi-Ship Problem

It was Jim Townsend's objective to find a new and effective method of modeling the targeting process in an anti-ship missile defense problem, and he has done so. The important consideration of screen design, whether in defense of a High Value Unit or for the purposes of shared defense, is one that has not received much play in model design. Screen design is still practiced in the fleet today, and within this thesis has been shown to demonstrate effect.

All of the points discussed in and at the conclusion of the Single Ship section of this chapter are also relevant here. Therefore, with careful selection of values for the many variables in play, the user can obtain a reasonable outcome to his simulations.

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V. CONCLUSIONS

The primary purpose of this thesis was to examine the utility of a recently developed but untested event-step model, the goal of which was to accurately model missile kinematics and the manner by which the missile chooses its target. Anti-ship missile defense is a sizable and complex problem, and the U.S. Navy is always interested in discovering models that can help to meet the ASCM threat. To assess the utility of this model, the author conducted an expansive set of simulations for the end purpose of understanding how the model behaves and what variables have the greatest or least impact on the modeled task force. It was also deemed important to check some of those results against real-world expectations to determine the validity and consistency of the model. These goals were accomplished in two ways, the first by running simulations involving a missile exchange with a single ship. The second method was to run a series of simulations involving a multi-ship formation followed by application of the lessons learned from the single-ship study. Any interesting insights divined from the generated data were commented on as well.

A. COMMENTS REGARDING MODEL PERFORMANCE

1. The Original Threat: Exocet

The original threat ASCM to be applied to this study was based on the Exocet, a subsonic, low-flying missile that is found in many inventories around the world. It was chosen by the author precisely because it has proliferated so widely and was a credible threat to U.S. Navy warships. The initial set of simulations involved an Aegis cruiser armed with SM2ER defending against Exocet attacks. Raid sizes were set at realistic values of two, four, and eight. The results, however, were very disappointing. An Exocet scored a hit against the cruiser only once every 75 trials, and only in cases where the raid size was greater than four ASCMs.

Townsend conducted limited simulations with the ASMD model, namely a four-ship screen design of which one of the ships was a CVN occupying the center of the screen. A cruiser was positioned directly ahead of the CVN, while two DD 963s were stationed abaft of the carrier. Applying a subsonic threat based on the Silkworm missile, Townsend found penetration of the screen for the purpose of achieving a hit against the CVN to be virtually impossible, contending the cruiser fired too fast for a Silkworm to get by. The only way a hit on the carrier could occur was by firing off-axis, or to overwhelm the defense with salvo sizes equal to 100. Even then, hits occurred only when firing at the DD 963s. (Townsend email of October 4, 2000)

The superb performance of the defensive missile systems as demonstrated by the Exocet results and the Townsend simulations (particularly the use of 100 missile salvos) did not bode well for future applications of the ASMD model. Real-world systems simply are not that effective. However, the vigorous exercise of the model, as done in this study with the single-ship problem, has demonstrated that methods can be employed to mitigate the ASMD model's weaknesses. The primary determinant of a threat ASCM's success is its speed, and in this case, employing a Mach 2.5 missile yielded 30 hits for every 75 trials. In addition, altering the performance of sensors to provide a less than perfect detection capability is bound to balance the results of the missile exchange.

2. ASCM Attrition by Fuel

ASCM attrition by fuel depletion is included in the data collection process, and when running the Exocet scenarios, this data appeared entirely reasonable because of the infrequency of attrition by fuel. Townsend also reported that he had not experienced any problems with this aspect of the model while running his scenarios (Townsend email of October 16, 2000). Within the model, each instance that the missile checks its position, it calculates the distance traveled up to that point.

When the transition in this study was made to the more survivable supersonic ASCM, the fuel attrition reports yielded an unusual result. Specifically, in each trial conducted, 40 – 60 percent of the ASCM raid consistently attrited due to fuel. The range of the ASCM launcher played no effect in this result. A threat missile with a 50 nm range would consistently attrite from fuel in the above percentages irrespective of the range to the target (15, 25, or 35). The source of the flaw within the model's code has not yet been identified, but it is likely that the problem went unnoticed in the Exocet portion of this study because the cruiser intercepted almost every ASCM fired. Fuel attrition is a nice characteristic to have in a model, and one that has not received much attention by other models but was successfully incorporated by Townsend. Since fuel attrition wasn't much relevant to the objectives of this thesis, a temporary solution was achieved for this study that involved disabling that feature of the ASMD model.

3. Data Collection Restrictions on a Modeled Ship with Multiple SAMs

Though it is possible to place more than one missile launcher on a ship, the model is not yet ready to collect data results for each specific missile system. Instead, the data collected on ASCMs killed would aggregate the results from the different SAMs used within a single trial. However, it is a feature that Townsend is working to incorporate in a future version of the ASMD model that will offer some great opportunities to do missile performance comparisons.

4. Simulation Run Time

Each time a scenario was run with a maximum of five trials, the simulation would last between five and ten minutes. Two constraints limited the number of trials that could be run. The first was that the volume of scenarios to be simulated was quite large, so trials had to be kept at a minimum. These time requirements exerted great drag on the process of running simulations, particularly if an error was found after the fact or fundamental changes to the scenario had to be made.

The second problem that surfaced and insisted on a five-trial minimum for each scenario run was due to a consistent tendency for the ASMD model to freeze up in mid-simulation. This effect resulted if the number of trials scheduled by the user within the executable portion of the model exceeded five. The root cause of this problem was never resolved, though there are suggestions that it relates to model design. It may be that the level of mathematical calculations involved in modeling missile flight are so great that the program grinds slowly to a halt, or the problem may relate to model design. It may be that the creation and destruction of java objects are not managed efficiently enough, and a different methodology might be necessary that would apply a recycling principle and/or reduce memory requirements.

5. ASMD Documentation

The ASMD model is very ambitious in its design, and could benefit from additional documentation within the java code so that the programmer's intentions can be fully understood. This issue was mitigated by regular communication with Jim Townsend. Were this not the case, it would have been extremely difficult for any person lacking significant java and simulation experience to successfully navigate the code.

B. MAIN CONCLUSIONS

The main conclusions regarding the ASMD model are the following:

1. The ASMD model is not yet a user-friendly tool. The code is not easy to follow or understand, and frequent communication and collaboration with Jim Townsend was a necessity. Not having a graphical user interface (GUI), in most cases a luxury, compels the user to delve deeply into the code to manipulate the necessary variables or augment the program in order to achieve the desired result.

2. Analysis of future missile systems can be undertaken, as was the case for ESSM and RAM in this study. It is entirely possible to begin with a set of details and expectations about a specific system, and then model the system so that the performance within the context of the simulation will be reasonable.

3. Defensive missile systems have too great an advantage over threat ASCMs in the current incarnation of the ASMD model. The success rate for the modeled SM2ER, ESSM, and RAM systems was simply too high. The primary cause for the high effectiveness of these systems is the perfect detection and tracking capability modeled for the sensors.

4. Simulation of the multi-ship formation produced results that appear to be consistent with real-world tactics. Specifically, stationing a SAM shooter near the threat axis has a positive effect on defense. Some agreement could also be found regarding the range of the SAM shooter to the high value units, in that a shorter range yielded positive results.

5. Once the model is understood, it can quickly and easily be applied to address the concerns of the tactical commander. Oftentimes, overnight analysis is required when contingencies arise unexpectedly, and the ASMD model demonstrates the potential not yet fulfilled for application as a tactical decision aid.

C. RECOMMENDATIONS FOR FUTURE RESEARCH

The following list of recommendations is not exhaustive, but does offer some key suggestions for improving the ASMD model:

- Develop a GUI to increase the user friendliness of the model.

- Find the cause and eliminate the tendency of the model to freeze in mid-simulation. This may be a result of computational drag, or the non-optimal management of mover objects within the model.

- Level the playing field that exists between the defensive missile systems and the threat ASCMs. This can probably be accomplished by some combination of the following changes: (1) establishing a range-based Probability of Hit, (2) association of a stealth factor or characteristic to the ASCM that the model can respond to by inhibiting detection or tracking, or (3) modification of the current sensor properties to allow for stressors that complicate the detect-to-engage process.

- Associate an animation feature to the model, so that the objects (missiles and ships) can visually be observed on a display. This would permit another level of validation that would allow the user to determine that the model is behaving in a reasonable manner.

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LIST OF REFERENCES

1. Ousborne, D.R., “Ship Self-Defense Against Air Threats”, *Johns Hopkins APL Technical Digest*, Vol. 14, Number 2, 1993.

2. Graff, G.Y., “Naval Ship Self-Defense Weapon Littoral Warfighting Performance Issues”, Naval Surface Warfare Center, Dahlgren Division Technical Digest, pp. 98-107, 1999.

3. Hughes, W.P., Jr., *Fleet Tactics: Theory and Practice*, Naval Institute Press, Annapolis, MD, 2000.

4. Schulte, J. C., “An Analysis of the Historical Effectiveness of Antiship Cruise Missiles in Littoral Warfare”, Master’s Thesis in Operations Research, Naval Postgraduate School Monterey, CA, 1994.

5. Gould, J., “On Efficient Salvo Policies”, *Naval Research Logistics*, Vol. 31, pp. 159-162, 1984.

6. Jarek, M. M., “Vertical Launch System Loadout Model”, Master’s Thesis in Operations Research, Naval Postgraduate School Monterey, CA, 1988.

7. Cares, J. R., “The Fundamentals of Salvo Warfare”, Master’s Thesis in Operations Research, Naval Postgraduate School Monterey, CA, 1990.

8. Drennan, A. P., III, “A Coordination Policy for the NATO Seasparrow Missile and the Rolling Airframe Missile using Dynamic Programming”, Master’s Thesis in Operations Research, Naval Postgraduate School Monterey, CA, 1994.

9. Hughes, W.P., Jr., “A Salvo Model of Warships in Missile Combat Used to Evaluate Their Staying Power”, *Warfare Modeling*, Bracken, Kress, Rosenthal (Eds.), Wiley, pp, 121-143, 1995.

10. Townsend, J. R., “Defense of Naval Task Forces from Anti-Ship Missile Attack”, Master’s Thesis in Operations Research, Naval Postgraduate School Monterey, CA, 1999.

11. Stork, K. A., “Sensors in Object Oriented Discrete Event Simulation,” Master’s Thesis in Operations Research, Naval Postgraduate School Monterey, CA, 1996.

12. Arntzen, A., “Software Components for Air Defense Planning”, Master’s Thesis in Operations Research, Naval Postgraduate School Monterey, CA, 1998.

13. Flanagan, G., “Protecting the Battlegroup”, *Surface Warfare*, Vol. 24, Number 2, Mar/Apr 1999.

14. Gertz, W., “Russia Readies Warship for China”, *Washington Times*, July 12, 2000.

15. Nicholas, T., Rossi, R., *U.S. Missile Data Book, 2000*, 24th Edition, Data Search Associates, November 1999.

BIBLIOGRAPHY

1 Almeida, R., Gaver, D.P., Jacobs, P.A., “Simple Probability Models for Assessing the Value of Information in Defense Against Missile Attack”, *Naval Research Logistics*, Vol. 42, pp. 535-547, 1995.

2 Ancker, C.J., Jr., “The Stochastic Duel with Time-Dependent Hit Probabilities”, *Naval Research Logistics*, Vol. 31, pp. 363-371, 1984.

3 Arntzen, A., “Software Components for Air Defense Planning”, Master’s Thesis in Operations Research, Naval Postgraduate School Monterey, CA, 1998.

4 Barfoot, C.B., “Continuous-Time Markov Duels: Theory and Application”, *Naval Research Logistics*, Vol. 36, pp. 243-253, 1989.

5 Bracken, J., Brooks, P.S., Falk, J.E., “Robust Preallocated Preferential Defense”, *Naval Research Logistics*, Vol. 34, pp. 1-22, 1987.

6 Bracken, J., Falk, J.E., Tai, A.J., “Robustness of Preallocated Preferential Defense with Assumed Attack Size and Perfect Attacking and Defending Weapons”, *Naval Research Logistics*, Vol. 34, pp. 23-41, 1987.

7 Bracken, J., Kress, M., Rosenthal, R.E., “Introduction to the Special Issue on Air-Land-Naval Warfare Models”, *Naval Research Logistics*, Vol. 42, pp. 147-150, 1995.

8 Cares, J. R., “The Fundamentals of Salvo Warfare”, Master’s Thesis in Operations Research, Naval Postgraduate School Monterey, CA, 1990.

9 Cares, J.R., “The Fundamentals of Naval Warfare”, 1998.

10 Cares, J.R., Hoyler, M., “The Fundamentals of Force Protection”, 1998.

11 Drennan, A. P., III, “A Coordination Policy for the NATO Seasparrow Missile and the Rolling Airframe Missile using Dynamic Programming”, Master’s Thesis in Operations Research, Naval Postgraduate School Monterey, CA, 1994.

12 Farris, R.S., Hunt, R.J., “Battle Group Air Defense Analysis”, *Johns Hopkins APL Technical Digest*, Vol. 2, Number 4, 1981.

13 Gafarian, A.V., Ancker, C.J.,Jr., “The Two-on-One Stochastic Duel”, *Naval Research Logistics*, Vol. 31, pp. 309-324, 1984.

14 Gafarian, A.V., Manion, K.R., “Some Two-on-Two Homogeneous Stochastic Combats”, *Naval Research Logistics*, Vol. 36, pp. 721-764, 1989.

15 Gould, J., “On Efficient Salvo Policies”, *Naval Research Logistics*, Vol. 31, pp. 159-162, 1984.

16 Graff, G.Y., “Naval Ship Self-Defense Weapon Littoral Warfighting Performance Issues”, Naval Surface Warfare Center, Dahlgren Division Technical Digest, pp. 98-107, 1999.

17 Hughes, W. P., Jr., “The Military Worth of Staying Power”, Technical Report, Naval Postgraduate School Monterey, CA, 1994.

18 Hughes, W.P., Jr., “A Salvo Model of Warships in Missile Combat Used to Evaluate Their Staying Power”, *Naval Research Logistics*, Vol. 42, pp. 267-289, 1995.

19 Hughes, W.P., Jr., Fleet Tactics and Coastal Combat, 2nd ed., Naval Institute Press, 2000.

20 Jarek, M. M., “Vertical Launch System Loadout Model”, Master’s Thesis in Operations Research, Naval Postgraduate School Monterey, CA, 1988.

21 Kress, M., “The Many-on-One Stochastic Duel”, *Naval Research Logistics*, Vol. 34, pp. 713-720, 1987.

22 Kress, M., “A Two-on-One Stochastic Duel with Maneuvering and Fire Allocation Tactics”, *Naval Research Logistics*, Vol. 38, pp. 303-313, 1991.

23 Manor, G., Kress, M., “Optimality of the Greedy Shooting Strategy in the Presence of Incomplete Damage Information”, *Naval Research Logistics*, Vol. 44, pp. 613-622, 1997.

24 Nguyen, B.U., Smith, P.A., Nguyen, D., “An Engagement Model to Optimize Defense Against a Multiple Attack Assuming Perfect Kill Assessment”, *Naval Research Logistics*, Vol. 44, pp. 687-697, 1997.

25 Orlin, D, “Optimal Weapons Allocation Against Layered Defenses”, *Naval Research Logistics*, Vol. 34, pp. 605-617, 1987.

26 Ousborne, D.R., “Ship Self-Defense Against Air Threats”, *Johns Hopkins APL Technical Digest*, Vol. 14, Number 2, 1993.

27 Parkhideh, S., Gafarian, A.V., “General Solution to Many-on-Many Heterogeneous Stochastic Combat”, *Naval Research Logistics*, Vol. 43, pp. 937-953, 1996.

28 Parrott, N. R., “Anti-Ship Missile Defense: Back to the Drawing Board”, Master’s Thesis in Operations Research, Naval Postgraduate School Monterey, CA, 1992.

29 Roe, C.L., “The NATO Seasparrow Surface Missile System”, *Johns Hopkins APL Technical Digest*, Vol. 12, Number 4, 1991.

30 Roe, C.L., “An Operational Computer Program to Control Self Defense Surface Missile Operations”, *Johns Hopkins APL Technical Digest*, Vol. 12, Number 4, 1991.

31 Schulte, J. C., “An Analysis of the Historical Effectiveness of Antiship Cruise Missiles in Littoral Warfare”, Master’s Thesis in Operations Research, Naval Postgraduate School Monterey, CA, 1994.

32 Sherali, H.D., Lee, Y., Boyer, D.D., “Scheduling Target Illuminators in Naval Battle-Group Anti-Air Warfare”, *Naval Research Logistics*, Vol. 42, pp. 737-755, 1995.

33 Steigers, C. W., “A Critical Analysis of a Range Dependent Probability of Kill for the NATO Seasparrow Missile System”, Master’s Thesis in Operations Research, Naval Postgraduate School Monterey, CA, 1985.

34 Stork, K. A., “Sensors in Object Oriented Discrete Event Simulation,” Master’s Thesis in Operations Research, Naval Postgraduate School Monterey, CA, 1996.

35 Tanner, T., “Two Deceptively Simple Scheduling Criteria”, 67th Military Operations Research Society (MORS) Symposium, United States Military Academy, 23 June 1999.

36 Townsend, J. R., “Defense of Naval Task Forces from Anti-Ship Missile Attack”, Master’s Thesis in Operations Research, Naval Postgraduate School Monterey, CA, 1999.

37 Van Dongen, M., Kos, J., “The Analysis of Ship Air Defense: The Simulation Model SEAROADS”, *Naval Research Logistics*, Vol. 42, pp. 291-309, 1995.

38 Wagner, D.H., Mylander, W.C., Sanders, T.J., Naval Operations Analysis, 3rd ed., Naval Institute Press, 1999.

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   Johns Hopkins University Applied Physics Lab
   Laurel, Maryland
   ronald.farris@jhuapl.edu

5. Professor Wayne P. Hughes, Code OR/HL
   Naval Postgraduate School
   Monterey, California
   whughes@nps.navy.mil

6. Professor Arnold Buss, Code OR/BU
   Naval Postgraduate School
   Monterey, California
   abuss@nps.navy.mil

7. Mr. Urey W. Patrick III
   Winterport, Maine
   sw10mm@aol.com

8. LT Chase D Patrick
   USS PAUL HAMILTON (DDG 60)
   Pearl Harbor, Hawaii
   Hoos94@gateway.net